EUFORIE

European Futures for Energy Efficiency

Work Package 3 - Deliverable 3.1

# Regional case studies of energy efficiency in Europe. Analysis of the energy efficiency barriers at the regional level.

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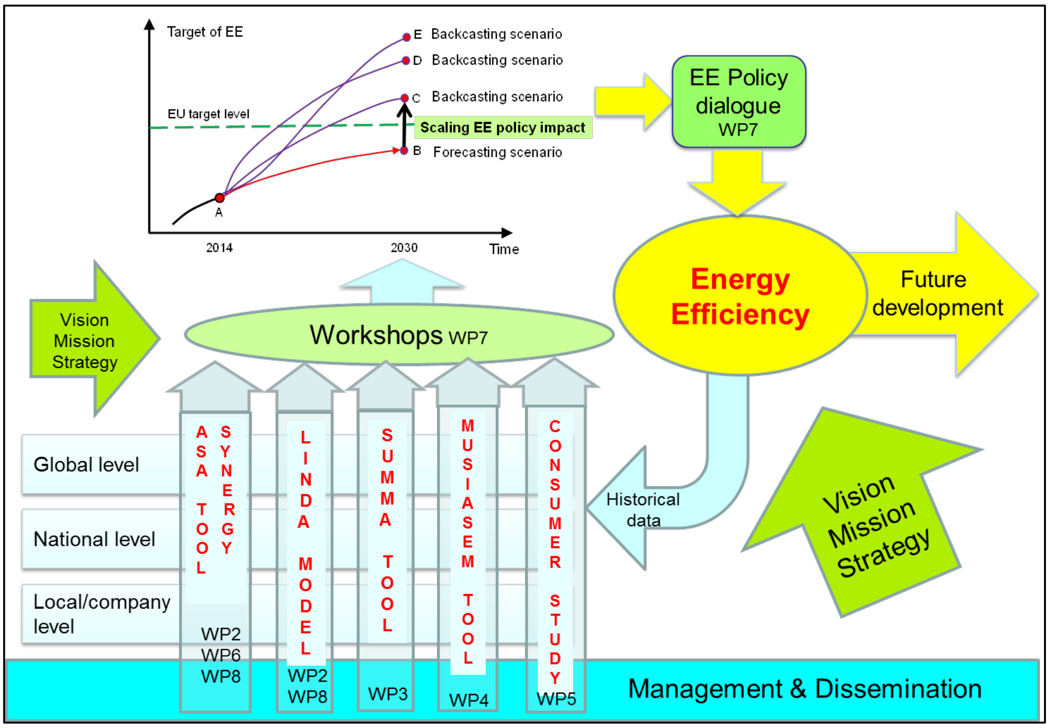
## The EUFORIE project

The strategic goal of the EUFORIE project is to provide useful and accurate information and knowledge in the field of energy efficiency for the EU Commission and stakeholders in the Member States. The tangible objectives are the following:

1. To provide energy and energy efficiency trends and their drivers, synergies and trade-offs between energy efficiency related policies, as well as energy efficiency scenarios (WP2).
2. To provide data about implementation of energy efficiency in specific processes, sectors and entire systems, in order to understand bottlenecks/efficiency drops and suggest improvements (WP3).
3. To carry out analyses of efficiency of provision, from making useful energy carriers from primary energy sources, and from conversion of energy carriers to end uses across macro-economic sectors (WP4).
4. To identify policy instruments and other measures leading to significant reduction in the energy consumption of households (WP5).
5. To analyse the relationship between investments and change in energy efficiency, and to develop indicators to describe changing energy efficiency at the company level (WP6).
6. To carry out participatory foresight for European stakeholders of energy efficiency with a target of providing ideas for the energy efficiency vision and strategy in the European Union (WP7).
7. To compare energy efficiency policy instruments and measures and their impacts in China and the European Union (WP8).

The EUFORIE Work Packages relate to each other The project applies different quantitative and qualitative analysis methods to energy efficiency in the EU and its Member States at different levels and from different perspectives. These analyses provide input for foresight activities, which serve European energy efficiency vision and strategy process by generating useful information. Management (WP1) and dissemination (WP9) run in parallel with the research and innovation activities.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Vision Mission Strategy
Workshops WP7
Global level
National level
Local/company level
ASA TOOL
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# Executive Summary

### *The goals of this deliverable*

WP3 aims at providing a sufficient set of data about implementation of energy efficiency. In particular, focus was placed and will be placed on specific processes, sectors and entire systems where energy plays a dominant role, in order to understand bottlenecks and efficiency drops and suggest alternatives or improvements. The goal of the study is:

* Understanding the role played by energy demand and energy quality. Identifying the present energy efficiency and the phases where efficiency drops occur (Tasks 3.1, 3.2 and 3.3)

* Identifying a set of potential solutions for energy efficiency improvement. Identifying environmental, material and energy costs and benefits, constraints and barriers to the implementation of such solutions. (Task 3.4)

* Assessing the potential of larger scale and EU scale implementation of proposed solutions, through geographical exploration of needs, potentials and constraints as well as scenario making over time. (Task 3.5)

* Exploring the potential integration of the different approaches into a standard procedure for policy making. (Task 3.6)

In the present deliverable D3.1 we only address Tasks 3.1, 3.2 and 3.3 and start addressing the topic of stakeholders involvement, as foreseen by Task 3.4. In fact, data collection and development of performance indicators aim at providing a transparent description of the investigated cases and, more than that, at showing that there are suitable methods to do so in a way that can be managed by interested stakeholders. The UNECE (*United Nations Economic Commission for Europe)* Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters, usually known as the Aarhus Convention, signed on 25 June 1998 in the Danish city of Aarhus by a large number of countries and the EU as well, and entered into force on 30 October 2001, foresees the right of citizens to access environmental information about every development that may affect their life. This way to achieve an environmental governance emphasizes a trustworthy relationship between civil society and governments and increases participation to the decision making process, in so promoting a so-called "governance-by-disclosure" (Aarti, 2008[1]).

Therefore, according to the goals of the EUFORIE project as well as the goals of the WP3, our activity addressed a number of case studies where efficient use of both

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[1] Aarti, Gupta (2008). "Transparency under scrutiny: Information disclosure in Global Environmental Governance". *Global Environmental Politics*. **8** (2): 1–7. doi:10.1162/glep.2008.8.2.1

material and energy resources plays an important role. The goal was to provide an insight into:

a) The interplay of material and energy efficiency;
b) The needed focus on the functional unit, namely the product of or the service provided by the process or system investigated;
c) The need for appropriate monitoring and assessment methods and performance indicators and their suitability depending on the spatial and time scale of interest;
d) The need to go beyond monodimensional energy assessments, that prove not to be very telling in the presence of complex systems and multi-input/multi-output processes;
e) The potential synergic integration of different (and more comprehensive than just energy) assessment methods;
f) The large set of processes, systems and activities where performance assessment is important and needs to be performed in a transparent way, in order to become the basis for discussion, understanding and quality improvement.

Providing a reliable picture of selected processes and systems may offer increased understanding of the need for preventive assessments of any new development as well as of the environmental, economic and social consequences of actions that invest resources, energy and know-how in production and consumption processes.

Although it is unthinkable to have a full and deterministic picture of every process, yet it is undeniable that resource assessments provide a framework to aware policies and decision-making.

Concerning the above identified topics, this Deliverable provides contributes as following.

*a) The interplay of material and energy efficiency.*

Energy efficiency has always been a difficult and sensitive concept, in that increasing efficiency does not always mean saving energy (Jevon paradox and rebound effect). As a consequence, although nobody would deny in principle the importance of energy saving, yet the majority of stakeholders seem more inclined towards making more energy available by means of renewable sources and devices, instead of designing a society that uses less energy as such. Not only saving energy is associated by many to a lower standard of living, but it is very frequent that the energy saved (or the saved money) is invested in other production and consumption activities to support growth and wealth. Since there is embodied energy in manufactured materials, a potential opportunity for energy saving can be associated to reuse and recycling. This option was recently expanded to the concept of circular economy, where full or partial recycling of matter is linked to less energy use, less environmental degradation and less mineral mining and processing. As a consequence, talking of energy efficiency is an incomplete exercise if not associated to material efficiency. We provide in this deliverable several examples of processes where energy, material and environmental benefits are clearly coupled.

b) *The needed focus on the functional unit, namely the product of, or the service provided by, the process or system investigated;*

Limiting the concept of efficiency to its thermodynamic value would be a nonsense in terms of policy making. The goal is to create a clear link between the material and energy investments and the process product or service provided. Only if a well defined functional unit is referred to for each investigated case or aspect where policy decisions are needed, comparison becomes possible and processes can be improved or placed in the appropriate context. Goal and scope definitions, allocation procedures, process diagram or flow-sheet, intermediate steps and products are therefore mandatory aspects to be addressed in support of resource and environmental policy-making.

c) *The need for appropriate monitoring and assessment methods and performance indicators and their suitability depending on the spatial and time scale of interest;*

The EUFORIE project aims to understand how energy and material resources can be effectively used to achieve goals of development and well-being in society. Therefore, the definition of the pursued target is of paramount importance and the "efficiency' cannot be assessed without doing so. In short, what we aim to is answering to the following questions: "efficiency to do what?", "efficiency at what scale ?", "efficiency for how long ?", "efficiency to whom? ", which raises questions about the goals, the spatial and time scales and the final beneficiaries of the achieved or pursued material and energy efficiency. Moreover, it is well known that efficiency is not achieved once for ever and that it is always possible to detect efficiency drops. Sometimes, efficiency increases due to innovations in some of the process steps, but innovation may be followed by a performance decrease as a consequence of changes in the system or decreased interest on targets due to economic or other reasons. As a consequence, steady monitoring of specific performance indicators is mandatory, in order to explore the possibility of steady improvements to counter potential decreases. In so doing innovation and steady improvements may be coupled and act synergically.

d) *The need to go beyond monodimensional energy assessments, that prove not to be very telling in the presence of complex systems and multi-input/multi-output processes;*

Mass flow accounting, energy accounting, monetary accounting are characterized by a mono-dimensional focus, namely only monitor material, energy and money flows. In complex systems of production and consumption, trade-offs are the most frequent case, where achieving an improvement of energy efficiency may require to decrease the material or the environmental or the sustainability performance of the system (e.g. due to the need to use rare minerals, so that the energy efficiency is negatively affected by environmental burden and toxicity due to more intense excavation of overburden and earth crust). Without losing track of energy flows and performance indicators, we have most often expanded our focus to Life Cycle Assessment as well as to Emergy

Accounting, in order to achieve a more comprehensive picture in our investigated cases and also suggest more complex assessment tools be adopted by policy-makers for effective monitoring and actual understanding of trade-offs.

e) *The potentially synergic integration of different (and more comprehensive than just energy) assessment methods;*

Being aware that each assessment method as well as related performance indicators have been purposefully designed to answer specific quastions at appropriate spatial and time scales, we understand that it is impossible to address all production and consumption as well as economic aspects by only relying on one method and one indicator. However, expanding the set of methods may also be a slippery way, in that their databases may be different and the actual application may pay different attention to aspects such as quality and origin of data, uncertainty, boundary conditions, among others. As a consequence, moving away from monodimensional assessments does not just mean adding one method to another, but requires deep understanding of the premises of each method and efforts to integrate them into an organized and consistent toolkit, where the same set of source data is used, and the same or consistent assumptions are made.

f) *The large set of processes, systems and activities where performance assessment is important and needs to be performed in a transparent way, in order to become the basis for discussion, understanding and quality improvement.*

Society is a complex network of production and consumption activities, linked to each other over interacting supply and trade chains. Not necessarily the energy efficiency improvement in one point of the network (e.g. due to recycling or resource exchange or circular economy patterns implementation) translates into an overall efficiency improvement at the level of the entire system; in a like manner, the abatement of one kind of impact (energy depletion, water depletion, land demand, emissions, etc) translates into an overall abatement of system's impacts. Most often, improvements are offset by increased burden in another point or component of the system. As a consequence, transparent information about individual processes or sectors needs to be linked to the entire set of other processes, in order to be able to move from local to global scale and viceversa, across scenarios and consequencial assessments, from deterministic to holistic understanding, from linear to decomposition analysis. Stakeholders need a complete set of data, links and scenarios, in order to be able to reache the above referred to "governance-by-disclosure". Most often discussion, dialogue, participatory governance, and appropriate problem-solving processes are prevented by lack of suitable information, so that decision-making processes translate into "talking of nothing". On the other side, when a too large dataset and number of case studies is presented, non-expert audiences are confused so that too much information becomes no-information at all. Therefore, our goal is to provide data and case studies in a way that they can be understood, managed and integrated also by non-experts among stakeholders. In order to do so, diagrams, figures, tables are accurately featured in a way that they are self standing and self explanatory. Within this Deliverable, case studies arising from the activities supported by the EUFORIE funding are linked and compared to other case studies and frameworks from previous or parallel research activities, not to lose possible synergic effect.

The contents of the present deliverable will be reconsidered and tailored in the future project activities, in order to provide the expected methodological and policy improvement planned for the Tasks 3.4, 3,5, 3.6. According to Task 3.4. Cost of solutions (to be reported at month 34), the efficiencies of investigated case studies and their critical steps (efficiency drops) were assessed and discussed with involvement of stakeholders and multicriteria experts, in order to understand solutions (if any) for higher energy efficiency. While this is not fully part of the present Deliverable, yet we partially report about some aspects under the title "Chapter 11. Energy Efficiency and Stakeholders", in order to start identifying the main problems related to participatory strategies (acceptance to be involved, knowledge of the problem, potential conflict prevention).

***The contents of this Deliverable***

In the following of this Deliverable we address a number of case studies.

**CHAPTER 1: ENERGY AND ENVIRONMENTAL EFFICIENCY IN AGRICULTURE AND LIVESTOCK FARMS**

***Chapter 1.a Italian Agriculture Across Time and Space Scales – Comparison with agricultural systems in Scotland and Poland - Decomposition Analysis and identification of major drivers of change.***

Chapter 1.a refers to ongoing research about Italian agriculture and agricultural processes in Scotland and Poland. This research started within a previous EU project (SMILE, 7th Framework Program), was enriched by collaborative links with Scottish and Polish partners, and finally synergically interacted with Task 3.1 of EUFORIE project. Results allowed to develop performance indicators for material and energy resource use in agriculture, suitable for comparison and planning.

***Chapter 1.b Chemicals from biomass: technological versus environmental feasibility towards appropriate material and energy resource use.***

Chapter 1.b was developed within the framework of the EUFORIE project (resource efficiency and environmental benefits of biomaterials extraction from agricultural substrates). Results were published in the paper: Gabriella Fiorentino, Maddalena Ripa and Sergio Ulgiati, 2016. Chemicals from biomass: technological versus environmental feasibility. A review. Biofuels, Bioproducts and Biorefining, 11: 195-214. Appropriate acknowledgement to the EUFORIE project is provided.

**CHAPTER 2: WASTEWATER TREATMENT.**

***Energy efficiency and recycle patterns scenarios for urban wastewater and sewage sludge treatment.***

Chapter 2 was developed within the framework of the EUFORIE project and results were published in the paper: Elvira Buonocore, Salvatore Mellino, Giuseppe De Angelis, Gengyuan Liu, and Sergio Ulgiati, 2016. Life cycle assessment indicators of urban wastewater and sewage sludge treatment. Ecological Indicators, Available online 20 May 2016, ISSN 1470-160X, http://dx.doi.org/10.1016/j.ecolind.2016.04.047, (http://www.sciencedirect.com/science/article/pii/S1470160X16302291). Acknowledgement to the EUFORIE funding is provided.

**CHAPTER 3: WASTE-TO-ENERGY**

***Chapter 3.a Recycling Waste Cooking Oil into Biodiesel***

Chapter 3.a deals with research developed within the Parthenope team based on Departmental sources of funding. This provided an interesting comparison opportunity with other research activities developed within the EU project EUFORIE. For this reason, Chapter 3.a was added to this Deliverable.

***Chapter 3.b Power generation from animal by-products***

Chapter 3.b was developed within the framework of the EUFORIE project and results were published in the paper: R. Santagata, M. Ripa, S. Ulgiati, 2017. An environmental assessment of electricity production from slaughterhouse residues. Linking urban, industrial and waste management systems". Applied Energy, 186(2): 175-188. Acknowledgement to the EUFORIE funding is provided.

**CHAPTER 4: PAPER-MAKING AND PAPER-RECYCLING INDUSTRY.**

***Efficiency and sustainability indicators for papermaking from virgin pulp. An emergy-based case study***

Chapter 4 was developed within the framework of the EUFORIE project and results will be published as: Corcelli F., Ripa M., Ulgiati S., 2017. Efficiency and sustainability indicators for papermaking from virgin pulp. An emergy-based case study. To be submitted to Journal Cleaner Production. Acknowledgement to the EUFORIE funding is provided.

**CHAPTER 5: URBAN WASTE MANAGEMENT.**

***The case of waste management in the Metropolitan City of Naples (Italy)***

Chapter 5 was developed within the framework of the EUFORIE project and results were published in the paper: M. Ripa, G. Fiorentino, V. Vacca, S. Ulgiati, 2017. The relevance of site-specific data in Life Cycle Assessment (LCA). The case of the municipal solid waste management in the metropolitan city of Naples (Italy). Journal of Cleaner Production, 142(1): 445-460. Acknowledgement to the EUFORIE funding is provided.

**CHAPTER 6: TRANSPORT MODALITIES AT URBAN AND REGIONAL LEVELS.**

***Chapter 6.a Terrestrial transport modalities in China: a survey of monetary, energy and environmental costs.***

Chapter 6.a was developed within the framework of the EUFORIE Project and results will be published as: Shupei Huang and Sergio Ulgiati, 2017. Terrestrial transport modalities in China: a survey of monetary, energy and environmental costs. To be submitted to Transport Policy, https://www.journals.elsevier.com/transport-policy. Appropriate acknowledgement to the EUFORIE funding is provided.

***Chapter 6.b Electric bike implementation.***

Chapter 6.b was developed by the research team within a different EU funding scheme. Results about energy efficiency and LCA of an electric bike provide an interesting complement to the results achieved in the EUFORIE project. For this reason, the Chapter was added to this Deliverable.

***Chapter 6.c Terrestrial transport modalities in Italy. A benchmark.***

Chapter 6.c was developed by the research team thanks to the support of other sources of funding. Considering the potential for synergic understanding and comparison of energy and material efficiency in transport modalities, the Chapter was added to this Deliverable.

**CHAPTER 7: ELECTRIC AND ELECTRONIC WASTE MANAGEMENT AND RECYCLING.**

***Chapter 7.a Energy and eMergy evaluation of production and operation of a personal computer. Focusing on advantages of recycling.***

Chapter 7.a was developed within the framework of the EUFORIE Project and results were published in the paper: Antonio Puca, Marco Carrano, Gengyuan Liu, Dimitri Musella, Maddalena Ripa, Silvio Viglia, Sergio Ulgiati, 2017. Energy and eMergy assessment of the production and operation of a personal computer. Resources, Conservation and Recycling, 116: 124-136. Acknowledgement to the EUFORIE funding is provided.

***Chapter 7.b Life Cycle Assessment of a recycling process for crystalline silicon photovoltaic panels end-of-life***

2. Chapter 7.b was developed within the framework of the EUFORIE Project and results were published in the paper: Fabiana Corcelli, Maddalena Ripa, Enrica Leccisi, Viviana Cigolotti, Valeria Fiandra, Giorgio Graditi, Lucio Sannino, Marco Tammaro, Sergio Ulgiati, 2016. Sustainable urban electricity supply chain – Indicators of material recovery and energy savings from crystalline silicon photovoltaic panels end-of-life. Ecological Indicators, Available online 5 April 2016, ISSN 1470-160X, http://dx.doi.org/10.1016/j.ecolind.2016.03.028, (http://www.sciencedirect.com/science/article/pii/S1470160X16301327). Acknowledgement to the EUFORIE funding is provided.

**CHAPTER 8: FOOD CHAIN.**

***A survey on the energy sustainability of urban agriculture towards more resilient urban systems***

Chapter 8.a was developed within the framework of the EUFORIE Project and results were published in the paper: Ghisellini P. and Casazza M., 2016. Evaluating the energy sustainability of urban agriculture towards more resilient urban systems. Journal of Environmental Accounting and Management, 2016, 4(2): 175-193. Acknowledgement to the EUFORIE funding is provided.

**CHAPTER 9: ENERGY AND MATERIAL EFFICIENCY IN BUILDINGS**

***Chapter 9.a Energy Efficiency in Universities. The case study of Palazzo Pacanowsky, Napoli, Italy***

Chapter 9.a is a Summary of the activity developed within Parthenope University by the Energy Efficiency Committee instituted by the Academic Senate (Prof. Sergio Ulgiati, Prof. Laura Vanoli and Prof. Pierluigi Caramia). Results were delivered as an internal Report to the Rector of the University, in order to implement energy saving strategies. This Summary is added to the deliverable because it provides a clear picture of energy efficiency problems within a real University building.

***Chapter 9.b – Material Efficiency in Buildings. Exploring environmental and economic costs and benefits of a circular economy approach to construction and demolition materials.***

Chapter 9.b was developed within the framework of the EUFORIE Project and results will be published as: Ghisellini P., Ripa M. and Ulgiati S., 2017. Material Efficiency in Buildings and related energy savings. Exploring environmental and economic costs and benefits of a circular economy approach to construction and demolition materials. To be submitted to Journal Cleaner Production. Acknowledgement to the EUFORIE funding is provided.

**CHAPTER 10: URBAN ENERGY METABOLISM.**

***Chapter 10.a Indicators of resource efficiency, environmental loading and sustainability of urban systems. An emergy-based environmental footprint.***

Chapter 10.a was developed within the framework of the EUFORIE Project and results will be published as: Silvio Viglia, Gianluca Cacciapuoti, Dario Civitillo and Sergio Ulgiati, 2017. Indicators of environmental loading and sustainability of urban systems. An emergy-based environmental footprint". Submitted to Ecological Indicators and accepted with minor changes. Acknowledgement to the EUFORIE funding is provided.

***Chapter 10.b Monitoring trends of urban development and environmental impact of Beijing, 1999–2006***

Chapter 10.b is the outcome of the collaboration of Prof. Sergio Ulgiati with Colleagues of BNU Beijing Normal University, China, on the topic of efficient use of resources in urban systems. This collaboration was developed over the last three years 2013-2016, since Prof. Ulgiati was selected as "Foreign Expert" by the Chinese Government and started to teach part-time at BNU. The activity partially paralleled the EUFORIE project activities described in Chapter 10.a, and provided synergic understanding of energy, environmental and material resources problems in urban systems, also serving as a benchmark for comparison. For this reason, Chapter 10.b was added to the Deliverable.

**CHAPTER 11: ENERGY EFFICIENCY AND STAKEHOLDERS.**

***A survey on awareness, willingness and barriers affecting the approach of stakeholders to energy efficiency implementation***

Chapter 11 is part of the PhD Thesis "Communicating the environment. How to manage scientific information and socio-economic aspects within a framework of stakeholders involvement and conflict prevention", submitted by Chiara Vassillo to the Parthenope University in partial fulfillment of the requirements for the PhD degree in "Environment, Resources and Sustainable Development". Chiara Vassillo took officially part of several activities and meetings of the EUFORIE Project and her travelling and mission expenses were supported by Project funds. In her Dissertation, acknowledgement to the EUFORIE project is provided.

**CHAPTER 12: NATIONAL AND REGIONAL ECONOMIES.**

***Chapter 12.a Social metabolism of Scotland: an environmental perspective.***

***Chapter 12.b Identifing the environmental support and constraints to the Chinese economic growth – an application of the Emergy accounting method.***

***Chapter 12.c Wealth, trade and the environment: carring capacities, economic performance and wellbeing in Brasil and Italy.***

Chapters 12.a,b.c summarize a number of research tasks developed within the Parthenope team in collaboration with other Partners worldwide. They were not developed within the framework of the EUFORIE funding, although biophysical assessment methods (energy, emergy and LCA) of national economies are core topics of the Parthenope team and are the basis of a large number of research activities performed in several EU funded projects, including EUFORIE. The goal is to provide an integrated tool that allows to monitor progresses towards better use of resources and compare different national economies based on their resource efficiency and environmental performances.

**CHAPTER 13: ENERGY EFFICIENCY IN ITALY**

***Global and sector-based focus on energy efficiency in Italy (task 3.2).***

This Chapter offers a quick overview of the energy efficiency in Italy in the main sectors of the economy (agriculture, industry, residential) as well as in the service sectors (mainly, transportation) with focus on savings achieved by means of increased energy efficiency. Data come from literature survey.

**List of papers published within the EUFORIE project**


**1.** Gabriella Fiorentino, Maddalena Ripa and Sergio Ulgiati, 2016. Chemicals from biomass: technological versus environmental feasibility. A review. Biofuels, Bioproducts and Biorefining, 11: 195-214.

3. Elvira Buonocore, Salvatore Mellino, Giuseppe De Angelis, Gengyuan Liu, and Sergio Ulgiati, 2016. Life cycle assessment indicators of urban wastewater and sewage sludge treatment. Ecological Indicators, Available online 20 May 2016, ISSN 1470-160X, http://dx.doi.org/10.1016/j.ecolind.2016.04.047, (http://www.sciencedirect.com/science/article/pii/S1470160X16302291).
4. R. Santagata, M. Ripa, S. Ulgiati, 2017. An environmental assessment of electricity production from slaughterhouse residues. Linking urban, industrial and waste management systems". Applied Energy, 186(2): 175-188.
5. M. Ripa, G. Fiorentino, V. Vacca, S. Ulgiati, 2017. The relevance of site-specific data in Life Cycle Assessment (LCA). The case of the municipal solid waste management in the metropolitan city of Naples (Italy). Journal of Cleaner Production, 142(1): 445-460.
6. Antonio Puca, Marco Carrano, Gengyuan Liu, Dimitri Musella, Maddalena Ripa, Silvio Viglia, Sergio Ulgiati, 2017. Energy and eMergy assessment of the production and operation of a personal computer. Resources, Conservation and Recycling, 116: 124-136.
7. Fabiana Corcelli, Maddalena Ripa, Enrica Leccisi, Viviana Cigolotti, Valeria Fiandra, Giorgio Graditi, Lucio Sannino, Marco Tammaro, Sergio Ulgiati, 2016. Sustainable urban electricity supply chain – Indicators of material recovery and energy savings from crystalline silicon photovoltaic panels end-of-life. Ecological Indicators, Available online 5 April 2016, ISSN 1470-160X, http://dx.doi.org/10.1016/j.ecolind.2016.03.028, (http://www.sciencedirect.com/science/article/pii/S1470160X16301327).
8. Ghisellini P. and Casazza M., 2016. Evaluating the energy sustainability of urban agriculture towards more resilient urban systems. Journal of Environmental Accounting and Management, 2016, 4(2): 175-193.
9. Marco Casazza, Gengyuan Liu, Sergio Ulgiati, 2016. The Tenth Planetary Boundary: To What Extent Energy Constraints Matter. Journal of Environmental Accounting and Management 4(4): 399-411.
10. Xu Tian, Yong Geng, Sergio Ulgiati, 2017. An emergy and decomposition assessment of China-Japan trade: Driving forces and environmental imbalance. Journal of Cleaner Production 141: 359-369.
11. Yong Geng, Xu Tian, Joseph Sarkis, Sergio Ulgiati, 2017. China-USA Trade: Indicators for Equitable and Environmentally Balanced Resource Exchange. Ecological Economics 132: 245–254


Papers No. 9-10-11 are not discussed in the present Deliverable. They pertain to large-scale energy and matter transfer and management and will be discussed in the Deliverable D3.3, together with large-scale policy suggestions.

**List of papers submitted or to be submitted within the EUFORIE project**


1. Corcelli F., Ripa M., Ulgiati S., 2017. Efficiency and sustainability indicators for papermaking from virgin pulp. An emergy-based case study. To be submitted to Journal Cleaner Production.
2. Shupei Huang and Sergio Ulgiati, 2017. Terrestrial transport modalities in China: a survey of monetary, energy and environmental costs. To be submitted to Transport Policy, https://www.journals.elsevier.com/transport-policy.
3. Ghisellini P., Ripa M. and Ulgiati S., 2017. Material Efficiency in Buildings and related energy savings. Exploring environmental and economic costs and benefits of a circular economy approach to construction and demolition materials. To be submitted to Journal Cleaner Production.
4. Silvio Viglia, Gianluca Cacciapuoti, Dario Civitillo and Sergio Ulgiati, 2017. Indicators of environmental loading and sustainability of urban systems. An emergy-based environmental footprint". Submitted to Ecological Indicators.

**BOX 1 – Tasks of WP3 related to Deliverable D3.1**

**WP 3: Regional case studies of energy efficiency in Europe** (from the proposed project, slightly modified according to later agreements with the Coordinator)

**Description of work** (where appropriate, broken down into tasks), lead partner and role of participants
Implementation of case studies will be carried out by means of a strict interaction with relevant stakeholders, in order to ensure appropriate understanding of the problem and appropriate design of solutions.
**Task 3.1.** Process level (Contribution by: Parthenope University, SERI…)
3.1a. Agriculture and livestock farms
3.1b. Wastewater treatment plants
3.1c. Waste-to-energy plants (e.g. gasification, anaerobic digestion, boilers, animal residues and waste cooking oil recovery for energy)
3.1d. Paper-making and paper-recycling industry
**Task 3.2.** Activity sector level (Contribution by: Parthenope University, SERI…)
3.2a. Urban waste management
3.2b. Urban transportation (individual car, mass transport, commodity distribution)
3.2c. Higher Education: Energy use in universities *(merged with below task 3.3a)*
3.2d. Electric and electronic waste management and recycling
3.2e. Food chain (with special attention to industrial food manufacture)
**Task 3.3.** System level (Contribution by: Parthenope University, Autonomous University of Barcelona)
3.3a. Energy use in buildings: a selection of different typologies of buildings *(includes above task 3.2c)*.
3.3b. Urban energy metabolism: a selection of cities in the partner Countries.
3.3c. Main regional and national economies: a selection of regional and national systems in partner Countries.

**BOX 2 – Tasks of WP3 related to Deliverables D3.2 and 3.3**

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**Task 3.4.** Cost of solutions.

The efficiency of investigated case studies and their critical steps (efficiency drops) will be discussed with involvement of stakeholders and multicriteria experts, in order to understand solutions (if any) for higher energy efficiency. Solutions do not come for free. Environmental, material and energy costs and benefits, constraints and barriers to the implementation of solutions will be assessed (through LCA, emergy, MuSIASEM methods) with special attention to burden shift prevention. The energy cost for implementation of a given innovation may be higher that the energy benefits, or the environmental or social constraints may suggest to redesign or replace a given step or process.

**Task 3.5**. Large spatial and time scale cost and benefit assessment.

Identification of local or specific efficiency drops or improvements does not necessarily means that the same consequences or solution apply Europewide. The extension of the analysis and of the solutions to the larger national scale or to the EU scale over time will be performed, through geographical exploration of needs, potentials and constraints (via GIS mapping). Design of scenarios of benefits over time, through the ASA models, will be performed.

**Task 3.6.** Standards for assessments.

Exploring the potential integration of the different approaches into a standard procedure for policy making. Testing the synergic effect of providing a multiplicity of indicators designed for different purpose. Pointing out the added value of results confirmed by more than one approach, but also of results that some methods are unable to identify, while other do. In so doing a comprehensive and bold basis for policy can be provided.

**Deliverables**

Deliverable 3.1: Report & Database. Results of LCA, Emergy, MuSIASEM methods applied to cases in Tasks 3.1, 3.2, 3.3. Delivery: Month 20. Responsible: Parthenope University.

Deliverable 3.2 Report on costs of solutions, initial findings and work in progress. Delivery: Month 29. Responsible: Parthenope University

Deliverable 3.3: Report. Assessment of costs and benefits of energy efficiency solutions suggested and modelled in Tasks 3.4 and 3.4. Delivery: Month 34. Responsible: Parthenope University

Deliverable 3.4: Report. Standardization and integration of assessment methods focused on energy efficiency. Delivery: Month 38. Responsible: Parthenope University.

## List of Acronyms and abbreviations used

%REN = R/U: Fraction of emergy use that is renewable
AA: Area of Agricultural land cropped
ALOP: Agricultural Land Occupation Potential
CED: Cumulative Energy Demand
EC: European Commission
ED: Empower Density: emergy investment per unit of time and per unit of area (seJ $s^{-1}$ $ha^{-1}$)
EIR= F/(R+N): Emergy Investment Ratio
ELR= (R+N+L+S)/R: Environmental Loading Ratio
EPA: Environmental Protection Agency
ESI= EYR/ELR: Emergy Sustainability Index
EU-28: Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.
EYR= U/F= (R+N+F+L+S)/F: Emergy Yield Ratio
F: Emergy flows imported from outside (purchased) or supplied as feedback
FDP: Fossil Depletion Potential
FEP: Freshwater Eutrophication
FETP: Freshwater Eco-Toxicity Potential
GVP: Gross Production Value
GWP: Global Warming Potential
HTP: Human Toxicity Potential
ILCD: International Reference Life Cycle Data System Handbook
IRP: Ionizing Radiation Potential
ISO: International Organization for Standardization
JRC: Joint Research Centre
L: Labor directly applied to the process (hours, converted to their emergy units). In this study, the term labor is also used in the decomposition equations to refer to all hours applied directly and indirectly (labor + services) to support the agricultural production.
L&S: Labor and Services
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
LCT: Life Cycle Thinking
MDP: Metal Depletion Potential
MEP: Marine Eutrophication Potential
METP: Marine Eco-Toxicity Potential
N: Locally nonrenewable or slow-renewable emergy flow

NLTP: Natural Land Transformation Potential
ODP: Ozone Depletion Potential
PMFP: Particulate Matter Formation Potential
POFP: Photochemical Oxidant Formation Potential
POP: Total population of the investigated regions, to be fed by the agricultural products of regional agriculture
R: Locally renewable emergy flow
ReCiPe: methodology for Life Cycle Impact Assessment (LCIA)
S: Services: Indirect labor applied to the upstream processes that extract, refine and deliver goods to the investigated process. In general, services are quantified in terms of economic cost of indirect labor (€, $), converted to emergy units (seJ)
seJ: Solar emergy joule: unit used to quantify emergy flows
SETAC: Society of Environmental Toxicology and Chemistry
TAP: Terrestrial Acidification Potential
TEP: Terrestrial Eco-Toxicity
U: Total emergy supporting the process or system under investigation. Sometimes referred to as "total emergy used".
UEV = U/output: Unit Emergy Value. Generic expression of emergy investment per unit of product of reference flow (seJ $g^{-1}$; seJ $€^{-1}$, etc). When the product is measured in energy units (J), the UEV is more frequently termed transformity (seJ $J^{-1}$)
ULOP: Urban Land Occupation Potential
WDP: Water Depletion Potential
Y: Yield. A measure (gram, joule, kwh, €, etc) of the process product.

**Energy Units**

PJ – Peta Joules ($*10^{15}$)

TJ – Tera Joules ($*10^{12}$)

GJ – Giga Joules ($*10^{9}$)

MJ – Mega Joules ($*10^{6}$)

## INTRODUCTION

### 1. Topics of interest for the EUFORIE project

WP3 aims at providing a sufficient set of data about implementation of energy efficiency. In particular, focus was placed and will be placed on specific processes, sectors and entire systems where energy plays a dominant role, in order to understand bottlenecks and efficiency drops and suggest alternatives or improvements. The goal of these case studies is:
a) Understanding the role played by energy demand and energy quality. Identifying the present energy efficiency and the phases where efficiency drops occur (Tasks 3.1, 3.2 and 3.3)
b) Identifying a set of potential solutions for energy efficiency improvement. Identifying environmental, material and energy costs and benefits, constraints and barriers to the implementation of such solutions. (Task 3.4)
c) Assessing the potential of larger scale and EU scale implementation of proposed solutions, through geographical exploration of needs, potentials and constraints as well as scenario making over time. (Task 3.5)
d) Exploring the potential integration of the different approaches into a standard procedure for policy making. (Task 3.6)
e) Implementation of case studies will be carried out by means of a strict interaction with relevant stakeholders, in order to ensure appropriate understanding of the problem and appropriate design of solutions (Task 3.4)
Therefore, the present Deliverable 3.1 deals with above point (a) "understanding" and (e) "stakeholders involvement". The latter should be dealt with in full within the Deliverable 3.2, but it seems appropriate to start reporting what is already being made. The remaining aspects pertain to the next deliverables.

### 2. Material and Energy Efficiency

The efficiency concept may be looked at under several different points of view as well as time and spatial scales.
Conceptually, efficiency suggests same results (products, services) be achieved with less input flows (material, energy, labor), or, vice versa, better results (more products, more services) be achieved with the same effort (same materials, same energy, same labor). Things may become even more complex from a conceptual point of view if focus is not placed on the amount of input or output flows, but instead (or also) on the quality of input and output flows. This is when, in addition to the raw amounts the assessment looks at the impacts of resource use as well as at their environmental quality or environmental generation dynamics.
The Work Package activities have therefore focused on different aspects that can be summarized as follows:

**2.1 Energy efficiency: how energy efficiency concepts emerge within a specific case study, process, system.** In particular:

2.1.a) Identify which input flows carry more energy and how this can be addressed and decreased (process design improvement, distance from flow source, flow replacement, etc).
2.1.b) Identify which process steps are the most energy demanding and how this can be addressed (process design, distance and transport issues, machinery replacement, etc).
2.1.c) Identify useless steps and options for their removal.
2.1.d) Identify still usable waste energy flows (e.g.: residual heat) and co-generation potential in process (i.e.: adding new co-products).
2.1.e) Identify options to increase the output flow without increasing the input demand, by decreasing waste flows (i.e.: feedback flows, cascade design, etc).

**2.2 Material Efficiency: how appropriate material use and recycling affect energy demand.** In particular:
2.2.a) Identify reuse and recycling impacts on process energy demand.
2.2.b) Identify material flows that carry the largest embodied energy.
2.2.c) Identify aspects of transport and distance (waste material collection, distance from mines, distance from disposal sites).
2.2.d) identify the most material demanding steps and their improvement potential (to be linked to the point 1.b above, about energy demanding steps).

**2.3 Quality Assessment versus efficiency. Replacement of input and output flows makes the system different and may generate burden shifts or affect the functional unit.** In particular:
2.3.a) Replacement of input flows is not just a matter of joules (one joule of oil versus one joule of coal versus one joule of solar), but involves the environmental work to generate a resource (time, ecosystem services, biosphere dynamics. This require focusing on biosphere replacement ability and embodied time. We address this by means of the eMergy method.
2.3.b) Replacement of input flows (be they primary energy, energy carriers or material flows) may help improve efficiency but generate burden shift. This can be addressed by means of Life Cycle Assessment.
2.3.c) Cogenerating two or more co-products, or re-designing a process towards different products or functional units may provide resource and environmental advantages, in that resources may be used more efficiently in a process than in another (e.g.: more efficiently in mass transportation processes than in individual transportation; more efficiently in providing a service – photocopies – than in supplying a product – a copy machine).

2.3.d) Full redesign of economic uses of resources (e.g. platform chemicals from biomass residues instead of platform chemicals from petrolchemistry; recycling of construction materials).

2.3.e) Comparison of performance indicators that are directly related to energy (Cumulative Energy Demand, Fossil Depletion, Carbon Emissions) and environmental performance indicators (eMergy indicators, soil use and soil use change, Water footprint, among others), in order to check if a higher energy efficiency was achieved by means of a burden shift affecting the quality of the surrounding environment. Actually, quantifying the trend of environmental indicators versus improvements of energy efficiency might provide a measure of the "marginal cost" of improving energy efficiency.

## 3. Cumulative Energy demand and Life Cycle Assessment (LCA)

LCA is a methodological framework to assess the potential environmental impacts and resources used throughout a product's lifecycle, from raw material acquisition, via production and use phases, to waste management (Figure 1). The methodological reference applied in this study is the LCA as defined by ISO and ILCD standards (International Standard Organization, ISO 14040/2006, ISO 14044/2006, ILCD, 2010a,b).

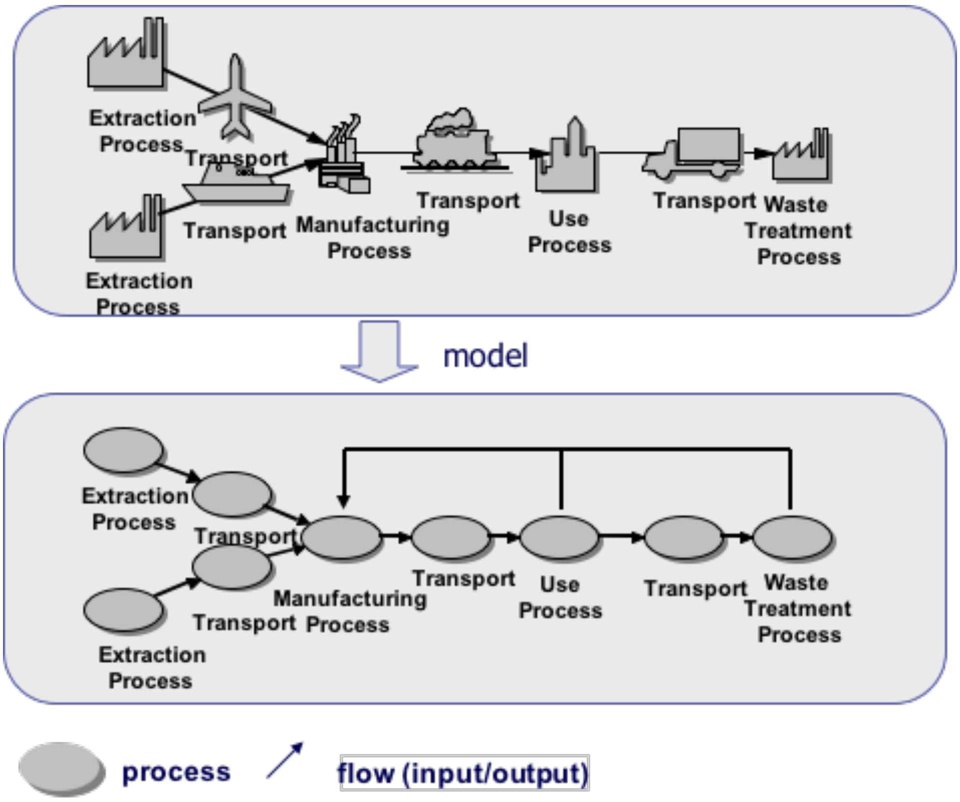


Figure 1. Cradle to Grave flow-sheet in LCA

All activities and processes result in environmental impacts due to consumption of

resources, emissions of substances into the natural environment, and other environmental exchanges. In other words, LCA looks at a process relation with the environment as a source and as a sink, and provides indicators related to many different environmental impact categories, such as climate change, stratospheric ozone depletion, depletion of resources, toxicological effects, among others. In the evaluation of a process, identifying "hot spots" facilitates prioritization of activities to improve its environmental performance. LCA allows technology comparisons in terms of material and energy efficiency and consequent environmental burden, providing valuable insights about the environmental performances of different technologies across categories. Although developments of the tool continue to be achieved, International Standards of the ISO 14000 series provide a consensus framework for standardized LCAs.
The ILCD Handbook, stemming from the ISO 14040/2006 and ISO 14044/2006 standards, confirms the importance and the role of LCA as a decision-supporting tool in contexts ranging from product development to policy making. The Handbook provides clear and goal-specific methodological recommendations, specific terminology and nomenclature, an accurate verification and review frame and other supporting documents and tools. The ILCD Handbook offers the basis for comparable and reliable LCA applications in business and public decision-making.
According to the ILCD handbook, an LCA consists of four phases (Figure 2):

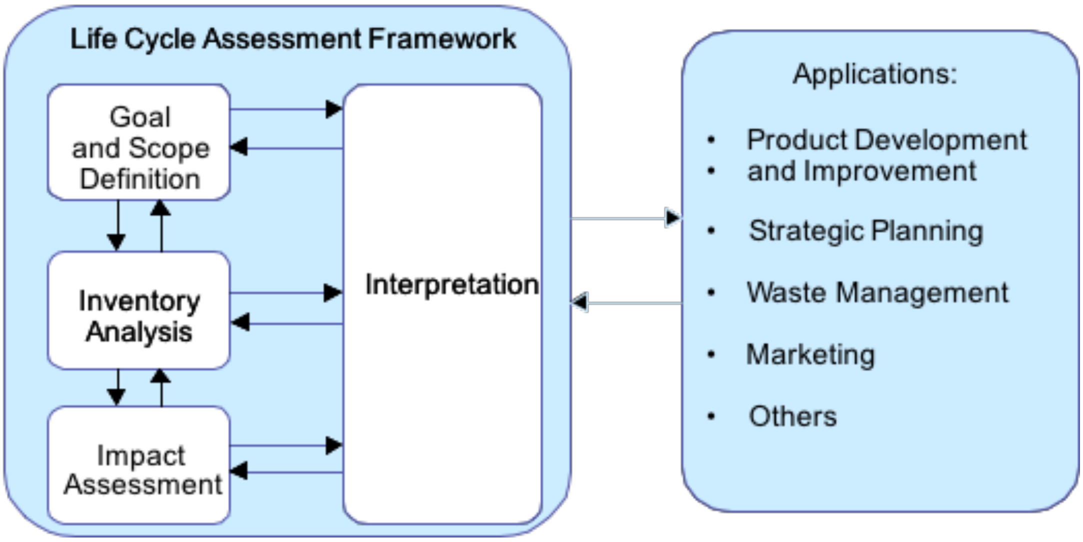


Figure 2. Interactive steps of LCA

1. Goal and scope definition phase, where the final goal of the LCA is stated and the central assumptions and choices in the assessment are identified. The goal definition is of paramount importance for all the other phases of the LCA, in that a clear, initial goal definition is essential for a correct later interpretation of the results.

2. LCI (Life Cycle Inventory) phase, where input and output flows of matter and

energy are quantified for the investigated process. For an LCA study, two types of data are usually required: specific inventory data on the foreground system, and average or generic data for the background system. It is important that all foreground and background data used in a LCA study are methodologically consistent and that the overall quality requirements for the analysed system are met.

3. LCIA (Life Cycle Impact Assessment) phase, where input and output flow data that have been collected and reported in the inventory are translated into indicators that reflect the pressure on environment and human health as well as the potential or actual resource scarcity. Calculation is based on factors which represent the contribution to an impact as emission or resource consumption per unit of product or service. The impact assessment analyses the potential environmental impacts caused by interventions that cross the border between technosphere and ecosphere and act on the natural environment and humans, often only after fate and exposure steps. The results of LCIA can be interpreted as environmentally relevant impact potential indicators.

4. Interpretation phase, where the results of the LCIA are interpreted in accordance with the goal of the study to answer questions posed in the goal definition. In this phase the significant issues are identified and evaluated in relation to their influence on the overall results of the LCA. Comparison among two or more systems may be involved. The interpretation is used to develop conclusions and recommendations.

The aim of an LCA study is to calculate the amounts of material and energy resources required, the emissions and waste generated, and the contribution to environmental impact categories per functional unit. The functional unit, that is a quantitative identification of the function/product of the studied system providing a reference to which the inputs and outputs can be related, is a key element of LCA that has to be clearly specified, so that all input and output flow can make reference to it. In an LCA of waste management the functional unit is generally defined in terms of system's input, i.e. the waste to be treated. All materials, emissions, costs, energy consumption, and recovery levels are referred to the selected functional unit.

Another important aspect of LCA is the distinction between attributional and consequential LCA. Attributional LCAs describe the environmental exchanges that are ‘attributed to’ the delivery of a specified amount of the functional unit. In contrast, consequential LCA refers to a description of the expected consequences of a change in the process or flow. It is an estimate of the system-wide change in pollution and resource flows that may result from a change in the investigated process. In this case, results may heavily depend on the magnitude of the change.

Among the impact assessment methods, the CML 2001 (Centre of Environmental Sciences of the Leiden University) and CED (Cumulative Energy Demand) are most often chosen. Recently, the ReCiPe midpoint (http://www.lcia-recipe.net/) emerged as an integrated impact assessment method that shows similar features as the CML2001 and C.E.D. jointly used.

The CML 2001 and the ReCiPe methods are used to assess the environmental impacts in different impact categories (e.g. global warming, abiotic depletion, acidification, eutrophication). The methods provide characterization factors to quantify the contribution to impact categories and normalization factors to allow a comparison across categories.
The CED method is applied to investigate the use of nonrenewable (fossil, nuclear, biomass from primary forests) and renewable (biomass from agriculture, wind, solar, geothermal, water) sources supporting the investigated process. It provides a measure of the energy costs to generate the functional unit. In the present study we focus on the amount of nonrenewable energy input required.
Finally, since a crucial limitation for a proper interpretation of LCA results is the existence of uncertainties and variations in the used data, the so-called Monte Carlo analysis is generally performed to address the uncertainty related to data collection and processing.

## 4. EMergy Accounting (EMA)

LCA studies are focused on matter and energy flows used under human control, while flows outside the market dynamics and flows which are not associated to significant matter and energy carriers (such as labor) are generally disregarded. Moreover, the time needed for resource generation within natural cycles (that is a fundamental parameter for their renewability) is not accounted for in LCAs. In order to better explore the performance and sustainability of a production process, such flows need to be also included.
In the present study, the Emergy method is used to expand the perspective of LCA by accounting for commercial energy inputs to the process (expressed in terms of the solar equivalent energy needed for their generation and processing), for the free renewable inputs provided by nature (sun, rain, wind, deep heat), for the different quality of inputs of materials, human labor, technology and economic services, and most of all for the time needed for resource regeneration by natural cycles.  All of these expressed on a common basis (solar equivalent energy), in so offering larger potentiality to explore the sustainable interplay of environment and economy. Emergy arguably offers the added value of a comprehensive donor-side assessment capable of providing an estimate of the total environmental support to a process.
Emergy is defined as "*the total amount of available energy (exergy) of one kind (usually solar) that is directly or indirectly required to make a given product or to support a given flow*" (Odum, 1996). The emergy concept of embodiment supports the idea that something has a value according to what was invested into making it.

This way of accounting for required inputs over a hierarchy of levels is defined a "donor system of value", while exergy and economic analyses are "receiver systems of value", i.e. something has a value according to its usefulness to the end user (or user's preferences). *Solar emergy* was therefore suggested as a measure of the total environmental support to all kinds of processes in the biosphere. Flows that are not from solar source (like deep heat and gravitational potential) are expressed as solar equivalents by means of suitable transformation coefficients (Odum, 1996).
The amount of input eMergy of the solar kind invested per reference (or functional) unit is named UEV (Unit Emergy Value) and measured as solar equivalent joule per unit (sej/J; sej/g; sej/ha; sej/hr; sej/€). Input and output flows related to the regional agricultural sectors and relevant for the emergy assessment are usually classified as locally available renewable and non-renewable flows, imported flows (services flows), economic flows. The emergy method takes into account not only the free environmental flows provided by Nature, but also the time needed for resource generation within biosphere processes as well as the economic flows of labor and services, to be considered measures of the societal infrastructures supporting the process. In so doing all aspects of sustainability (economic, social, environmental) are properly accounted for.
A computational table is designed, in order to group input flows according to their characteristics and to allow their conversion from conventional units (energy and exergy, J; mass, g; labor or services, US$, € or other currency) into emergy units (seJ). Such Table represents the numerical version of the emergy Equations (1) and (2):

$$U = \sum_i f_i * UEV_i \qquad (1)$$

$$UEV_i = U_i/f_i \qquad (2)$$

where U = Total Emergy (sej); $f_i$= different inflows to the system (as J, g, h and currency units); $UEV_i$= Unit Emergy Value (emergy invested per unit product or service) of the i-th flow (sej/J; sej/g; sej/h; sej/unit currency), with UEV of solar radiation assumed equal to 1 by definition.

The total emergy U calculated by summing up the emergies of all input flows, i.e. the total emergy invested into the process, provides a measure of the total biosphere work for (and environmental support to) the implementation of the process.[2]

[2] Prior to 2000, the annual emergy driving the geobiosphere was calculated as 9.44E+24 seJ/yr (Odum, 1996) as the sum of solar radiation, deep heat and tidal momentum (calculated as solar-equivalent amounts). Odum *et al*. (2000) recalculated the total emergy baseline as 15.83E+24 seJ/yr in order to include the co-action of solar, gravitational and geothermal sources. Previously calculated UEV values must be multiplied by 1.68 (the ratio of 15.83/9.44) for conversion to the new baseline. Brown and Ulgiati (2011) refined the calculation to 15.2E+24 seJ/yr, based on updated values and conversion of energy to exergy units. The emergy baseline is the reference for all main biosphere-scale processes, the UEV of which are calculated also under the assumption to put the UEV of solar radiation equal to

The ratio of U to the energy or mass of the product yields the new UEV of the product. The UEVs that result are useful for later emergy evaluations. The UEV is a measure of how much activity of the environment was required to provide a unit product: the higher the UEV of a product the greater the environmental work to produce it, the more valuable the product flow. So the UEV is an indicator of past environmental contribution to a specific resource production and use.

The main steps followed to perform the EMA of a process were:

I. Identification of the boundaries (spatial and temporal) of the study area.

II. Modeling of the investigated system through an emergy system diagram according to systems' diagramming language (Odum, 1996). (Example in Figure 3).

III. Calculation of matter, energy and money flows supporting the system.

IV. Conversion of the above flows into emergy units by using suitable UEVs.

V. Assessment of the total emergy used by the system.

VI. Calculation and interpretation of emergy-based indicators of environmental performance and sustainability.

A set of indices and ratios suitable for policy-making (Ulgiati *et al*., 1995; Ulgiati and Brown, 1998; Brown and Ulgiati, 1999; Brown and Ulgiati, 2004a, b) can also be calculated:

1) Total eMergy use, U= R+N+F. It measures the renewable (R), nonrenewable (N) and imported (F) emergy that converge to produce the yield (Y).
2) UEV= U/output. It measures how much emergy it takes to generate one unit of output, regardless of whether the input is renewable or not. According to the way it is defined and calculated, the UEV measures the global conversion efficiency over the whole chain of processes leading from primary resources to the final product.
3) Emergy Yield Ratio, EYR= (R+N+F)/F. It is a measure of the ability of a process to exploit and make available locally renewable (R) and nonrenewable (N) resources by investing outside resources (F). It is an index sensitive to the alternative local-imported.
4) Environmental Loading Ratio, ELR= (N+F)/R. It compares the amount of nonrenewable (N) and imported (F) emergy to the amount of locally renewable emergy sources (R). In a way, the ELR is a measure of the possible disturbance to the local environmental dynamics, generated by the development driven from outside sources. The ELR is clearly able to make a difference between nonrenewable and renewable resources, thus complementing the information that is provided by the UEV.
5) Emergy Investment Ratio, EIR= F/(R+N). It is a measure of the effectiveness of an investment to drive a local development. The same resource investment, depending on the process that is implemented, may make possible the exploitation of different amounts of local resources.

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1 seJ/J. All other UEVs of human-dominated processes are calculated accordingly, as ratios of the needed emergy input flows to the output flow(s).

6) Renewable Fraction of emergy use, %REN= R/U, the fraction of emergy use that is from local renewable sources. The ELR is linked to the %R, through the equation (3):

$$\%REN = R/(R+N+F) = 1/[(R+N+F)/R] = 1/[1 + (N+F)/R] = 1/(1 + ELR) \quad \text{Eqn. (3)}$$

7) Emergy Sustainability Index, ESI= EYR/ELR. It is an aggregated indicator of sustainability that links the characteristics of the EYR (sensitive to the outside-versus-local emergy alternative) and the ELR (sensitive to the nonrenewable-versus-renewable emergy alternative). It responds to the goal of relying on the largest possible amount of local resources in a process at the lowest possible environmental loading.

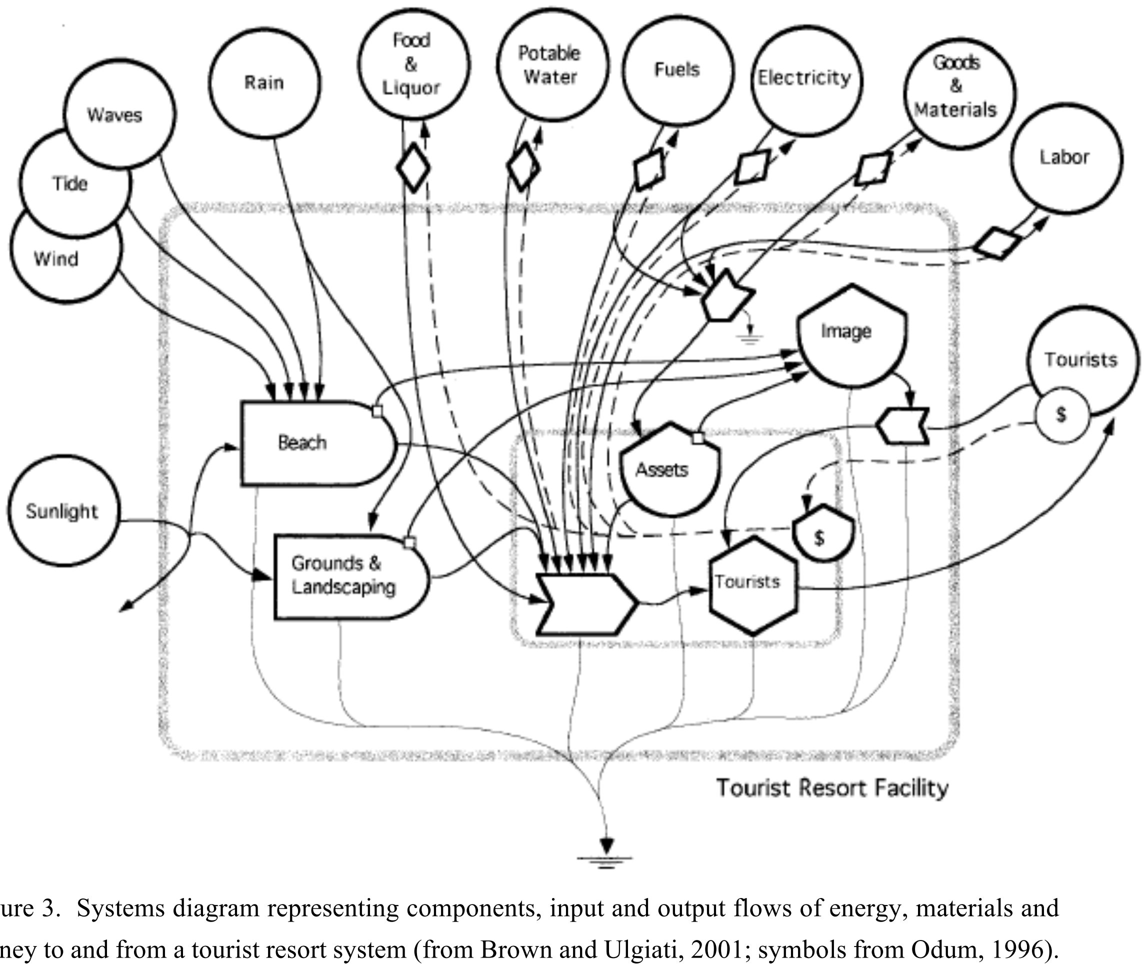


Figure 3. Systems diagram representing components, input and output flows of energy, materials and money to and from a tourist resort system (from Brown and Ulgiati, 2001; symbols from Odum, 1996).

Emergy can be considered the memory of the available energy invested, directly and indirectly, through a process to obtain a product or service. Therefore, an extended life cycle approach is implicit. However, EMA differs from Life Cycle Assessment (LCA, http://lct.jrc.ec.europa.eu/eplca) by its expanded spatial and time scales, as well as the inclusion of categories of input resource flows generally not accounted for by LCA. Moreover, emergy analysis is a donor-side approach focusing on upstream resources driving a process, while LCA is mainly focused on downstream impact categories that quantify the consequences of emissions and waste. The total emergy driving a process can be calculated with and without accounting for the emergy supporting inflows of Labor and Services (L&S). L&S flows bring into the accounting the economic dynamics of society, namely the emergy cost associated with information embodied in a skilled labor force as well as emergy supporting the indirect labor essential for production and delivery of materials, technology, and infrastructure.

## 5. Overcoming the inadequacy of single-criterion approaches to Environmental Assessment. The SUMMA framework.

SUMMA, SUstainability Multi-criteria Multi-scale Assessment, was developed by Ulgiati et al. (2011). The rationale of SUMMA is that investigating only the behavior of a single process and seeking maximization of one parameter (efficiency, production cost, jobs, etc.) is unlikely to provide sufficient insight for sustainable policy making. Instead, if suitable approaches are selected, applicable at different scales and designed so that they complement each other, integration would be feasible. Each method may supply a piece of information about system's performance at an appropriate scale, to which the others may not be applicable. Integration provides an overall picture, characterized by an 'added value' that could not be achieved through each approach individually. SUMMA, based on a unique set of input data to be used in the calculation of all indicators for increased consistency of results, is capable to expand the focus of the evaluation beyond the more traditional accounting of energy costs and environmental impacts.

The SUMMA inventory focuses on slow-renewable and nonrenewable material and energy flows, free environmental flows, environmental services, socio-economic data such as labor and economic services, and information flows such as DNA, culture, know-how – although the latter are very difficult to assess and quantify). Figure 4 shows a schematic overview of how the framework is applied. The Appendix of Deliverable 3.2 shows an example of "entry page" that is used for SUMMA. All data are entered through this inventory page and then processed within an in-house generated software based on an excel workbook. The software provides the entire set of SUMMA indicators. The same inventory can be used for MuSIASEM evaluations (see below) and the set of calculated indicators generated over a suitable number of years can be used for ASA decomposition analyses (see below).

The analyzed system or process is treated as a "black box" and a thorough inventory of all the input and output flows is firstly performed on its local scale. It is important to underline that this inventory forms the common basis for all subsequent impact assessments, which are carried out in parallel, thus ensuring the maximum consistency of the input data and inherent assumptions. Each individual assessment method is applied according to its own set of rules. The "upstream" methods are concerned with the inputs, and account for the depletion of environmental resources, while the

"downstream" methods are applied to the outputs and look at the environmental consequences of the emissions.
The main upstream methods in SUMMA are the Material Flow Accounting (Schmidt-Bleek, 1993; Hinterberger and Stiller, 1998; Bargigli et al., 2004), the Embodied Energy Analysis (Slesser, 1974; Herendeen, 1998) and the Emergy Accounting (Odum, 1988; Odum, 1996; Brown and Ulgiati, 2004); while the downstream methods mainly rely on all different kinds of assessment of the impact of airborne, waterborne and solid waste releases.

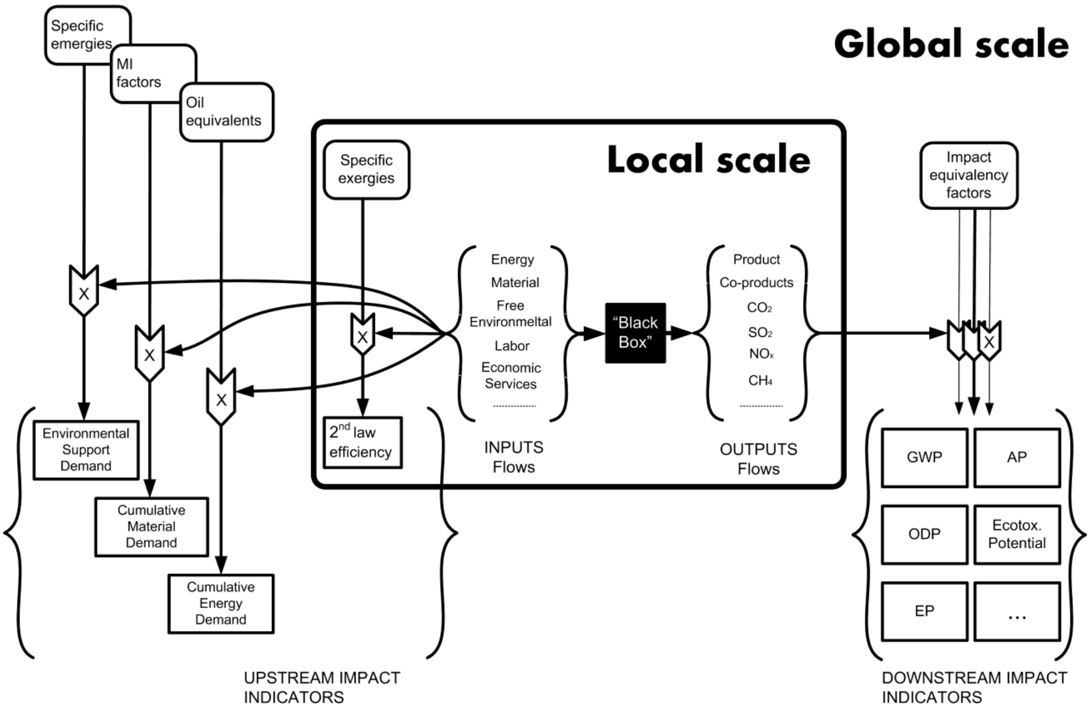


Figure 4. Flow diagram of the multicriteria multiscale approach LCA/SUMMA. The system is treated as a black box. Input and output flows are multiplied by specific exergy, energy, matter, emergy and emission factors to yield estimates of upstream and downstream impacts on resource and environmental dynamics (Ulgiati et al. 2006, modified).

Downstream methods may simply be stoichiometric evaluations of output chemicals (based on the assumption that "less is better"; or the characterization and equivalency of chemical releases for identification of specific LCA impact categories (e.g., the CML2 baseline 2000 method developed by the Centre of Environmental Science, Leiden University, NL, 2000); or finally, a damage-oriented, impact assessment method based on broader targets (human health, biodiversity, resources) as with Eco-indicator 99.
As previously mentioned, an important aspect taken into account by SUMMA is that each evaluation can be carried out at different space and time scales. In general, the local scale evaluation only accounts for direct energy and mass inputs flows (also including a system's assets and infrastructures, discounted over the system's lifetime). As the scale is expanded to the regional level, it includes the production processes for all system's components (machinery, building materials like concrete and steel, etc.)

so that additional mass and energy inputs must be accounted for. If the scale is further expanded, the mass of raw minerals that must be excavated to manufacture the pure metals for plant components also contribute to all the calculated performance indicators. The existence of a forced multi-level relation among hierarchical levels entails that any change in the level of consumption and investment of the whole society (energy consumption, water consumption, land use, labor flows, etc) must be reflected in a compatible integrated change in another part of the system (Giampietro *et al.*, 2010).

SUMMA considers the different aspects of environmental performance at different time and space scales. A selection of upstream and downstream methods is employed, offering complementary points of view on the complex issue of environmental impact assessment. As already pointed out, all methods rely on a common inventory (input and output mass flows, input and output energy flows, environmental flows and economic flows) that is used to calculate upstream (cumulative material demand, cumulative energy demand, and environmental support demand) and downstream LCA indicators (the main impact categories are: Global Warming Potential -GWP-, Acidification Potential -AP-, Eutrophication Potential- EP-etc.). In addition it is possible to calculate Socio-Economic indicators combining the total amount obtained from the Emergy Accounting and Embodied Energy Analysis, with the socio-economic raw amount. A more detailed survey of the SUMMA procedure is provided in Figure 5. A large inventory dataset is converted to impact assessment measures by means of characterization parameters. In particular, input mass and energy flows from the local inventory are converted to embodied mass and embodied energy amounts; the same mass and energy flows, plus the free environmental flows are converted to exergy units, used to calculate the exergy efficiency of the process, and then converted to emergy flows by means of appropriate emergy intensity factors.

Money flows of labor and services are also converted to emergy flows by means of economic emergy intensities from existing national emergy accounting databases. Output matter and energy flows from local inventory are converted to impact assessment estimates, by means of appropriate characterization factors. The cumulative matter, energy and emergy demands are divided by total GDP, land used, time invested and converted into global process performance indicators. Finally, the energy of the product (when applicable) and the mass of the product (when applicable) are divided by the cumulative mass and energy in order to calculate the LCA energy use efficiency and LCA matter use efficiency.

Multicriteria approaches support the solution of decision problem by evaluating the alternatives from different perspectives and by analysing their robustness with respect to uncertainty.

The raw data referring to the interaction of the socioeconomic system with its context are collected and entered into the SUMMA approach, where these raw data are transformed using several analytical methods into a set of indicators, referring to the impact on the environment and the efficiency in using resources in relation to specified goals. By characterizing both upstream and downstream interactions, SUMMA provides an analysis of the relevant flows that enter into and get out of the system or process treated as a "black box" (Figure 4).

When used in an integrated way, the different methods provide an overview of both the ecological constraints and the biophysical constraints that limit the performance space of socioeconomic systems. This is obtained by tracking the embodied input and output, using a system of accounting capable of tracking:

- the free services provided by the environment;
- the thresholds of environmental loading that should not be crossed to respect ecological compatibility.

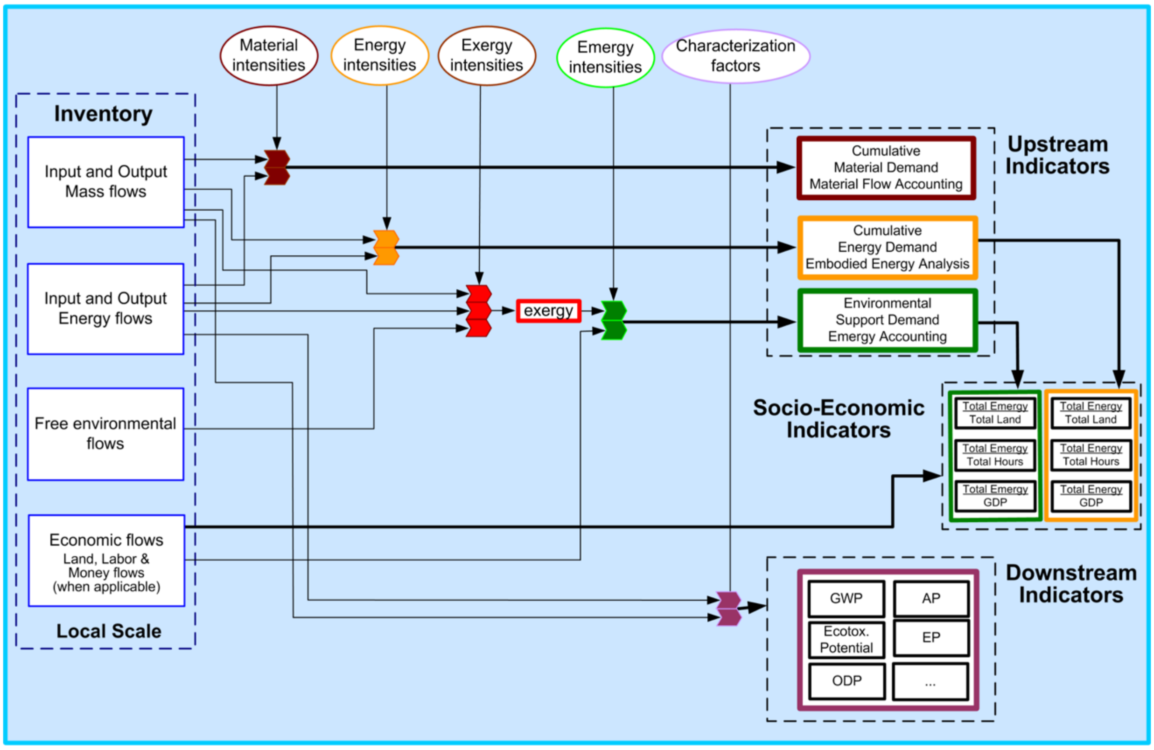


Figure 5. Flow chart of the multicriteria multiscale approach LCA/SUMMA.

SUMMA procedure is characterized by qualitative and mainly quantitative data. Both aspects must be taken into proper account, provided that the procedure is based on an agreement upon identification of the problems and the goal, a shared awareness of uncertainties that may affect the results as well as of the meaning of calculated indicators and finally a joint discussion of the results and their applicability.

The SUMMA approach is based on the parallel or sequential application of selected complementary methods, towards a more comprehensive picture of process performance and sustainability. It evaluates a process from several points of view, within a Life Cycle framework. SUMMA's procedure requires the calculation of a set of indicators that may be used directly or aggregately into macro-indices for policy making.

## 6. MuSIASEM and ASA: The added value of approach integration

A society-oriented approach, the MuSIASEM (Multi-Scale Integrated Analysis Societal Ecosystem Metabolism; Giampietro and Mayumi, 2000a; 2000b; Giampietro 2003) has also been developed to generate an evaluation tool capable of providing a quality control on quantitative analyses applied to the issue of sustainability. In particular, MuSIASEM analyzes the sustainability of social-economic systems by abandoning the conventional mono-scale analytical approach, used by the neoclassical economy to generate quantitative assessments of economic performance, and by moving to a multi-scale analysis. According to Giampietro's proposal, only in this way it becomes possible to gain further understanding on complex issues.
The approach has been developed with the explicit goal of establishing a linkage between representations and data referring to different scale and descriptive domains. The metabolism of socioeconomic systems (described in terms of the required throughput of energy, material flow and money for economic elements) can be analysed on at least three hierarchical levels: a) the national level (level n), which is the most comprehensive, dealing with the national dynamics of the economic system. The next lower level (level n-1) is obtained when making a distinction between two compartments related to the activities of production (activities generating added value, or paid work) and consumption (households). These two compartments compete for the given endowment of investments of human activity, technical capital and colonized land. A lower level (level n-2) is obtained when decomposing the aggregate investment of either the production compartment or the consumption compartment in subcompartments. The productive compartment can be split in the subsectors: agriculture, industry, mining and energy sectors; and services and government sector. The consumption compartment can also be split in different subcompartments: e.g. Urban versus Rural Households, in turn these can be split in different residential typologies. All these lower level compartments will have a typical metabolic rate of flows of added value, energy, and other critical material flows such as water, CO2, material waste, etc.. This approach integrates biophysical, ecological, economic, social, demographic and land use analyses, making it possible to handle simultaneously nonequivalent descriptive domains, across different scales. By taking into account simultaneously different views of sustainability MSIASEM can individuate constraints affecting development.

Preliminary studies applying a combination of SUMMA and MuSIASEM to different scales and systems have been already attempted in two different European projects (DECOIN, "Development and Comparison of Sustainability Indicators" and SMILE, "Synergies in Multi-scale Inter-Linkages of Eco-social systems"), where scenarios were also drawn based on ASA (Advanced Sustainability Analysis, Kaivo-oja *et al.*, 2001a and 2001; Luukkanen *et al.*, 2005), a decomposition analysis tool that helps identify the drivers of change in a time series of performance indicators.

The Advanced Sustainability Analysis (ASA) is a coherent mathematical framework for the analysis of the different dimensions of sustainability (see Fig. 6). The ASA approach provides new quantitative indicators such as dematerialisation of production, immaterialisation of consumption, rebound effect, sustainable economic growth level, welfare productivity etc. for the sustainability analysis and for comparison of different policy alternatives.

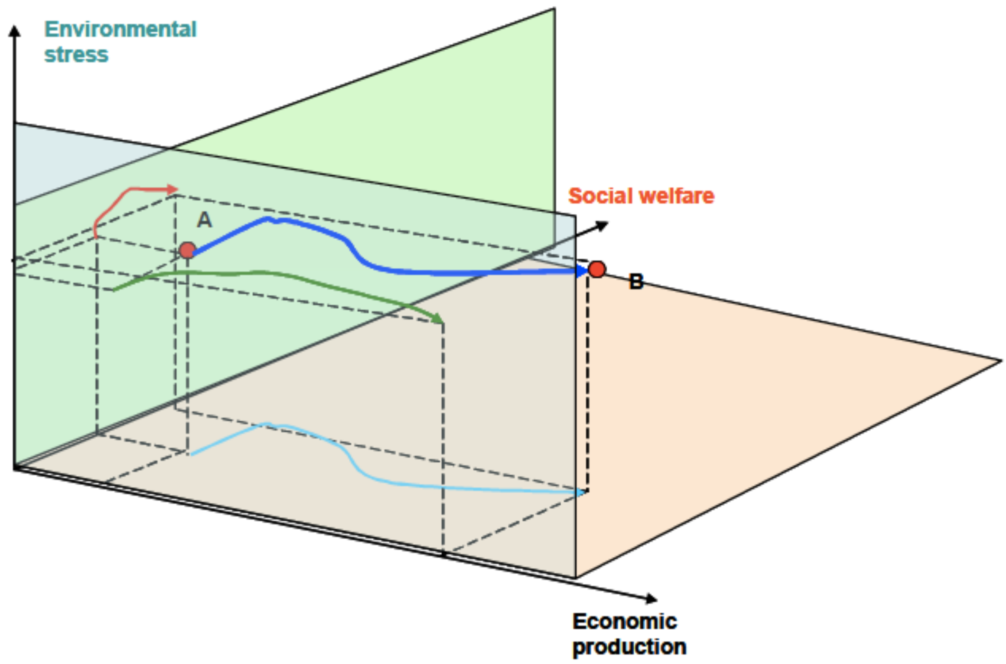


Figure 6. ASA analysis in the different dimensions of sustainability.

The ASA approach is used for analyzing different driving forces behind environmental, social or economic impacts, or other outcomes of human activities at different levels of society. The driving forces in the ASA approach can include different extensive factors like population and affluence (measured e.g. by economic output in different units) and intensive ones depending on e.g. technological development (typically intensities or/and efficiencies) or structural factors of the social processes, following the idea of the IPAT identity. The ASA approach can be utilized in comparative analyses of the different dimensions of sustainability and the interlinkages between them.

LCA, EMA, MuSIASEM and ASA share many similarities in the way they are applied: they start from model definition, are based on the same data inventory, and provide indicators that may help choices and improvement. They differ for the main goal of the investigation (impacts, environmental costs, constraints, and scenarios, which makes integration a profitable exercise. In the remaining part of the research activity of WP3, LCA and EMA integration will be mainly pursued, without disregarding in some case studies the advantage of inclusion of the other methods.

However, all of them can be easily integrated within the framework provided for LCA and ASA. (Figure 7)

When the different approaches (here, LCA and EMA) are suitably integrated and jointly applied, the following added values are also achieved:

A. Consistency of results: the same set of data is used for both approaches;

B. Comprehensiveness of investigated aspects: by adding a second set of input flows (environmental, labor and services) that are not included in the LCA the assessment does not limit to conventional resources such as fossil fuels and materials, but acknowledges the importance and the role of other resource categories, sometimes not even included in market economy evaluations;

C. Expanded focus: by developing indicators of performance and sustainability that refer to different "questions" and scales, the joint assessment provides a much more complete picture of the entire process.

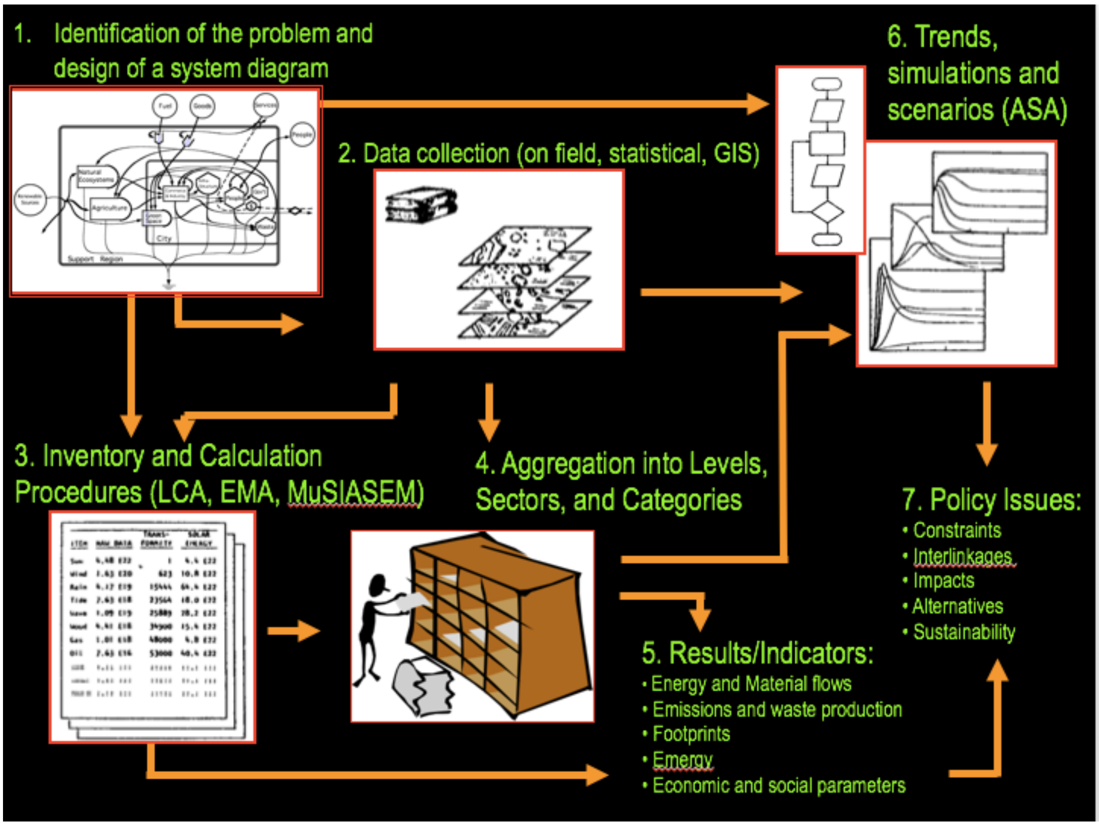


**Figure 7. Preliminary schematization of the approach integration, for policy making and participatory discussion.**

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# CHAPTER 1 – ENERGY AND ENVIRONMENTAL EFFICIENCY IN AGRICULTURE AND LIVESTOCK FARMS

## Introduction

The establishment of new patterns of socio-economic development is becoming, in recent years, a priority also in government policies at all scales. The main objective is to safeguard the productive sectors as well as to respect the environment and natural heritage, perceived as a real asset to be preserved also for the benefit of future generations. Agriculture is one of the sectors that require more attention, considering its fundamental task of meeting the nutrition needs of 7 billion humans on Earth. Appropriate resource use (energy and material efficiency as well as monetary benefits commensurate to resource investment) are crucial in the assessment of agricultural processes for healthy relation between societal food demand and ecosystem's ability to meet such needs.

A huge pressure is placed on agriculture and forestry in the hope photosynthesis can become the source of food, energy, fibres, construction materials, biomaterials (in particular biochemical in replacement of oil-derived chemicals. Such increasing demand due to an increasing population may translate into excess exploitation of arable land, land use change and related environmental problems, intensification or industrialization of agricultural activities, spread of genetically modified crops and, ultimately decrease, instead of increase, of resource efficiency in the agricultural sector.

We have performed a deep study about the above aspects of photosynthesis (solar energy) exploitation, addressing aspects of performance of agricultural and livestock production, aspects of relation between GMOs and resource efficiency, and finally aspects of energy and biomaterial extraction from the agricultural products as a way to save fossil energy.

Our agricultural performance study refers to the Italian agriculture at different scales (national, regional, individual farm), compared with case studies in other countries, in order to point out different performances and resource use efficiencies. We also compared the resource use performance in different agricultural systems and countries over time, in order to uncover the costs and benefits of subsistence, industrial and GM agricultures over time. Finally, we investigated the feasibility, resource efficiency and environmental advantages of biomaterials production from agricultural substrates, compared to their fossil counterparts. LCA and Emergy Accounting methods described in the Introduction were applied.

Chapter 1 deals with:

*Chapter 1.a Italian Agriculture Across Time and Space Scales – Comparison with agricultural systems in Scotland and Poland Decomposition Analysis and identification of major drivers of change.*

*Chapter 1.b Chemicals from biomass: technological versus environmental feasibility.*

## *Chapter 1.a*

*A. Italian Agriculture Across Time and Space Scales.*

*B. Comparison with Scottish agriculture.*

*C. Comparison with Polish agriculture. Environmental Assessment and comparison of Italian and Polish milk production.*

**D.** *Decomposition Analysis and identification of major drivers of change.*

**References**

## *A. Italian Agriculture Across Time and Space Scales*

The resource use and environmental performance of the Italian agricultural system were evaluated at three different levels (Figure 1.1):

- the Italian agricultural sector as a whole, hereafter referred to as *level* $n$+1;
- the Campania region (southern Italy), hereafter referred to as *level n*;
- selected individual farms in the Campania region, hereafter referred to as *level* $n-1$.

For levels $n$ and $n$+1 the evaluation is performed over time, i.e. monitoring the performance over selected years, based on official agricultural and economic statistics [ISTAT, 1985, 1993, 2002, 2006, 2012]. For level $n-1$ such a monitoring was not possible, because statistical offices do not provide annual records of environmental and energy data at the individual farm level.

Collected data refer to the total product of national, regional and local agriculture, quantified as dry mass, energy content and economic value as well as to the main input flows (renewables, fertilizers, machinery, fuels, water for irrigation, electricity, direct labor, indirect labor) supporting the agricultural systems in the investigated years.

*The national agricultural system (level n+1)*

Italian agriculture is highly developed, thanks to the high soil fertility, proper climate conditions and abundance of water, thus enabling a mixed variety of high-quality fruit and vegetable products. The northern part of Italy produces primarily grains, sugar beets, soybeans, meat, and dairy products, while the southern part specializes in fruits, vegetables, olive oil, wine, and durum wheat.

About 50% of the total agricultural area in Italy is covered by forage crops, out of which 30% permanent and 15% temporary, for livestock feed. The remaining land is covered by cereals (30%) and arboricultural crops (20%), among which the most important are olive (8%) and grape (6%) farms. Some farms also generate other typologies of product (e.g.: agro-tourism activities, biomass energy); however, these were not included in the assessment and therefore, the additional inputs of labor and resources for these activities were also not included.

The profile of Italian agriculture (productivity, energy intensity, machinery use, etc.) is in line with most Western European countries, because of the effects of the Common Agricultural Policy (CAP) of the European Union (EU). The CAP was not very successful in Italy in its initial stages because subsidies did not cover several traditional Mediterranean products such as olives, tomatoes, oranges, and lemons.

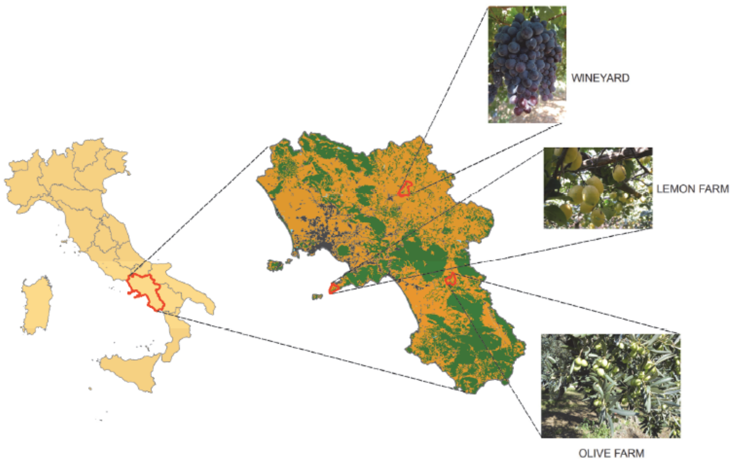


**Fig. 1.1** The investigated agricultural system, at three different scales: national (Italy), regional (Campania) and farm level (grape, olive and lemon farms).

When these crops were finally included, some positive aspects of the supporting policy emerged, together with conflicting interests deriving from market expansion and aggressive competition. Firstly, CAP provided the necessary capital for improvement of agricultural mechanization; second, it offered an incentive to merge too small farms and thus enlarge the average farm size. Finally, it ensured that most traditional Italian agricultural products were relatively protected in the economic global competition. Italy, also due to its climate and soil conditions, is a world leader in olive oil production and a major exporter of rice, tomatoes, and wine. The worldwide recognized quality of Italian food products, acknowledged and relatively protected by European regulations, is still an important driver of market leadership (for example, many Southern Italy wines expanded their markets thanks to improved production infrastructures and are now appreciated in Italy and abroad).
Although in the last twenty-five years the agricultural sector in Italy has been characterized by an increase of agricultural GPV (Gross Production Value; about 28% increase over the investigated period) and energy consumption (about 37% increase), yet at national level agriculture still plays a less important role compared to other economic sectors, contributing to only 6% of the national GDP.

*Campania region agriculture (level n)*

Campania is one of the most populous regions of Italy, well known worldwide for the ancient and rich history of its cities and the beauty of its landscape. It covers an area of 13,595 square kilometers and it is among the widest regions of Italy. The region is divided into five provinces: Napoli, Avellino, Benevento, Caserta and Salerno.
The most suitable land for agriculture is located near the coast (Tyrrhenian sea). These areas present favorable agricultural conditions and water availability, good rainfall rates and temperate climate (temperature from 0° to 30°C). The soils are volcanic and highly fertile. Due to fertile soil, water availability and favorable climate, Campania

ranks among the Italian regions characterized by highest agricultural productivity and quality. Our case study includes all the land cropped in Campania region (9.49 E+05 ha in 1985 and a lower 6.51 E+05 ha in 2010, including land used for animal fodder) with important land use oscillations in the 25 years investigated, mainly due to the urbanization process and the abandonment of rural areas.
The agricultural land of Campania region was 4.4% of total arable land of Italy (1.37E+07 ha) in the year 2006, used in this paper as the reference year for comparison across spatial scales. Productivity in terms of dry matter (g d.m./ha/year) was 20% higher in the regional agriculture than in Italian one, which translates into a 17% higher energy content of crop production as a whole (J/ha/year) of the delivered product and a gross production value that is about twice the average value per hectare in Italy [ISTAT, 1985, 1993, 2002, 2006, 2012]. This can be attributed to the favorable conditions previously referred to (volcanic soil, warm climate, abundant rainfall) and to a crop mix characterized by high market value (wine, oil, lemon, among others).
Forage production accounted for about 35% of the total land cropped in 1985, 44% in 2002 and seems to have stabilized around 43% in 2006 and later. Cereals (mainly wheat and corn) accounted for an average, slightly declining fraction of 22% of total cropped land. Olive production was about 9% of total agricultural land in 1985 with an increasing trend up to 11.6%. All kinds of fruit, citrus and nut trees globally accounted for about 12.2% in 1985, slowly declining to 11% in the following years. Other non-negligible sub-sectors are grape production (averaging 5% in the investigated period), tobacco (from 3.5% in 1985 to 1.6%), potatoes (from 3% in 1985 to 1.7%) and tomatoes (from 3% in 1985 to 0.9%). Forage provides support to the livestock sector, which is an important economic activity at the regional level. However, the livestock sector also imports feedstock from outside the region.

*Agricultural production in selected local farms (level n-1)*

The Campania region is known for high quality production of grapes, olives and lemon. These crops are important from two different points of view: economic production value ("limoncello" from lemon farm, olive oil from olive farm and wine from wineyard) and amount of land used. In fact, the land cropped dedicated for these crops is, more or less, 20% of the total cropped area in Campania region.
Furthermore, many quality labels are assigned to these products or their derivatives. Special quality labels (PGI, Protected Geographical Indication) are assigned by the European Union to the Sorrento "limoncello", a traditional liquor exported worldwide. The DCO (Denomination of Controlled Origin) and CGDO (Controlled and Guaranteed Denomination of Origin) are assigned to many Campania wines (Aglianico, Sangiovese, Piedirosso, Falanghina among others). Olive oil production is identified by the PDO (Protected Designation of Origin) with special focus on the production occurring in the Sorrento Peninsula and the Salerno Province. The investigated lemon, olive and grape farms are located respectively in the municipality of Massa Lubrense (Sorrento peninsula, province of Napoli), in the municipality of Contursi Terme (province of Salerno) and the last one in the province of Benevento.

**Results**

Results are organized in Tables and radar diagrams, where indicators are shown and compared. In order to compare data with different orders of magnitude in the same radar diagram, we applied normalization procedures in relation to different datasets (different years or different systems):

- Normalization with reference to the original dataset: all values are divided by the value of the original dataset (first year of investigation or reference scenario, Figures 1.2, 1.3, and 1.5).
- Normalization based on the standard score**:** each indicator calculated is subtracted by the arithmetic mean (μ) and divided by the standard deviation (σ) (Figure 1.4).

After the normalization procedure, the indicators can be displayed in a radar diagram, in such a way that a larger area in the diagrams suggests a higher relative impact. Data used in this study were provided by ISTAT (National Italian Statistical yearbooks for the years 1985, 1993, 2002, 2006, and 2010) as well as by local and regional agencies and statistical surveys as indicated by references [ISTAT, 1985, 1993, 2002, 2006, 2012].

*Results from the "n+1" level (national agricultural sector)*

The agricultural land in Italy decreased steadily (about 22%), from 1985 (1.70E+07 ha) to 2010 (1.33E+07 ha) and keeps decreasing. The total mass of agricultural product (as dry matter) also decreased, by about 37%%, from 1.25E+08 tons/yr (1985) to 7.84+07 tons/yr (2010). The productivity per hectare of Italian agriculture slightly oscillates over time around a value of 7.00 ton/ha/yr. This productivity is mainly due to the implementation of intensive practices (mechanization, fertilization, etc.) in the Italian agriculture, thus compensating the decrease of agricultural land. An inventory of input flows in the year 2006, based on the diagram of Figure 1.2 is shown in Table 1.1, chosen as a reference year for comparison with more recent land use. All flows are converted to emergy values, by means of suitable conversion factors (Unit Emergy Values, UEV) from literature or from our previous studies. After a similar calculation is performed over a selected set of years, a performance comparison can be carried out. The variation of the sector's performance over time is clearly affected by a mix of factors: rainfall oscillations and related variation of irrigation practices, decreased amount of arable land actually cropped, variation of the mix of crops, change in technology (increased agricultural machinery), decrease of labor, increased use of fertilizers and other chemicals. A large fraction of emergy costs is due to the resource investment in support to labor and services, i.e. to the direct and indirect activities displayed over the entire supply chain and societal network of infrastructures in order to make the process possible. Of course, the higher the standard of living in a society, the higher the emergy of labor and services [Franzese et al, 2009].

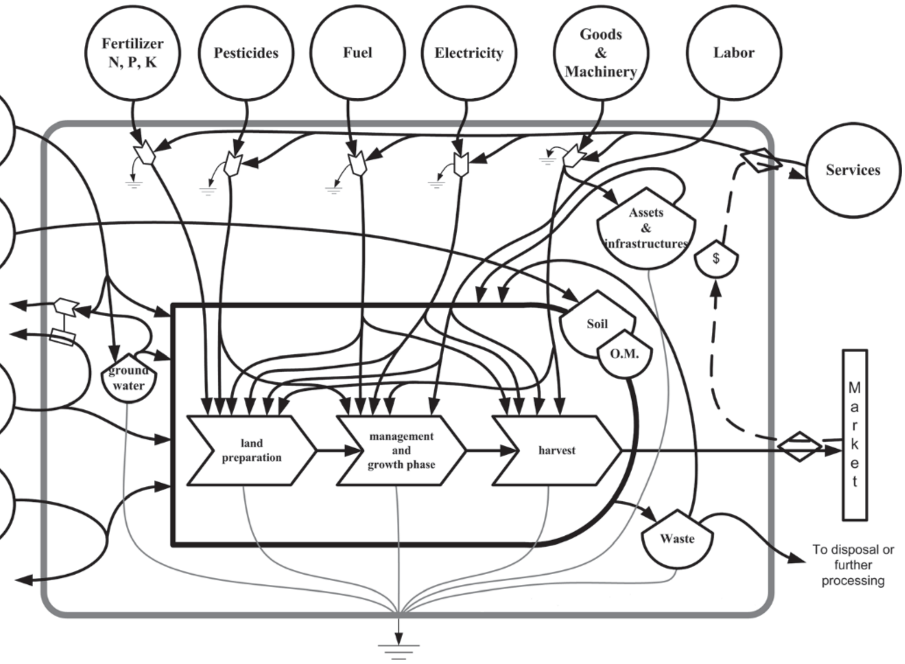


**Figure 1.2** a) System diagram showing the environmental and economic input flows to and from a generic agricultural system. b) Energy systems symbols from [Odum, 2000].

The radar diagram in Figure 1.3 provides a picture of increasing demand for environmental support over time and decreasing global resource use performance. The most important changes over the investigated period at the national level (Table 1.2), can be identified as:

- Increased use of fuels (23% in emergy units, from 1985 to 2010) and electricity (75% from 1985 to 2010), and consequent increase of local non-renewable emergy use, N (by 61%);
- Small increase of renewable emergy use (4%);
- Decrease of EYR from 1.14 in the year 1985 to 1.10 in the year 2010; increase of the ELR from 8.40 to 13.11; decrease of the ESI from 0.14 to 0.08; increase of all the emergy intensities (emergy/GPV, emergy/land, emergy/mass, emergy/energy) in the same period;
- Increase of the emergy associated to labor and services by 91%, as a clear link to improved standard of living.

The importance of labor and services as key factors of production processes is crucial and most often disregarded. For this reason, all the indicators are displayed in Table 1.1 also without L&S. The inclusion of L&S may hide the actual biophysical performance, namely the appropriateness of use of resources other than L&S (e.g., diesel, electricity, fertilizers). As a consequence, it is always very useful to compare indicators with and without L&S, in order to point out performance differences and oscillations.

**Table 1.1** Emergy Evaluation of Italian agriculture in 2006

| Items | Units | Raw Amount | Emergy Intensity (seJ unit-1) | Ref. Transf. | Emergy (× $10^{19}$ seJ yr-1) |
|---|---|---|---|---|---|
| Renewable Input | | | | | |
| Sun | J/yr | 5.85E+20 | 1 | [a] | 58.50 |
| Wind | J/yr | 2.37E+18 | 2.51E+03 | [b] | 594.03 |
| Rainfall | J/yr | 2.28E+17 | 3.05E+04 | [b] | 696.73 |
| Geothermal Heat | J/yr | 4.11E+17 | 1.20E+04 | [b] | 493.20 |
| Nonrenewable Input | | | | | |
| Top soil | J/yr | 9.39E+15 | 1.24E+05 | [b] | 116.19 |
| Imported Input | | | | | |
| Gasoline | | 2.50E+16 | 1.11E+05 | [b] | 276.52 |
| Diesel and heavy fuel | J/yr | 7.10E+16 | 1.11E+05 | [b] | 785.04 |
| Electricity | J/yr | 1.98E+16 | 2.81E+05 | [c] | 555.75 |
| Water for irrigation | J/yr | 2.35E+15 | 7.61E+05 | [d] | 178.81 |
| Fertilizers | g/yr | | | | |
| Nitrogen (N) | | 8.27E+11 | 6.37E+09 | [b] | 526.41 |
| Phosphate (PO4) | g/yr | 3.61E+11 | 6.54E+09 | [b] | 235.78 |
| Potassium (K2O) | g/yr | 2.94E+11 | 1.84E+09 | [b] | 54.14 |
| Fungicides | g/yr | 7.35E+10 | 5.08E+09 | [e] | 37.32 |
| Insecticides | g/yr | 2.28E+10 | 4.81E+09 | [e] | 10.96 |
| Acaricides | g/yr | 1.82E+10 | 8.25E+09 | [e] | 15.01 |
| Agricultural machinery | g/yr | | | | |
| *steel and iron* | | 1.78E+11 | 5.31E+09 | [f] | 94.52 |
| *aluminum* | g/yr | 3.04E+10 | 3.25E+10 | [b] | 98.82 |
| *rubber and plastic material* | g/yr | 2.17E+09 | 3.69E+09 | [b] | 0.80 |
| *copper* | g/yr | 6.51E+09 | 3.36E+09 | [c] | 2.19 |
| Human Labor | €/yr | 1.75E+10 | 2.75E+12 | [g] | 4810.12 |
| Indirect Labor (Services) | €/yr | 8.11E+09 | 2.75E+12 | [g] | 2228.53 |
| TOTAL EMERGY with Labor and Services | | | | | 10723.63 |
| TOTAL EMERGY without Labor and Services | | | | | 3684.98 |

*References for transformities: [a] [By definition]; [b] [After Odum, 2000; [c] Brown and Ulgiati, 2004; [d] [After Buenfil, 2000; [e] [Estimated from Biondi et al, 1989; [f] Bargigli and Ulgiati, 2003; [g] [After Cialani et al, 2005. Note: Unit Emergy Values refer to the 15.83E+24 seJ/yr baseline. All UEVs calculated earlier, based on the 9.44E+24 seJ/yr baseline, have been multiplied by 1.676 for update [Odum, 2000].

*Results from the "n" level (regional agricultural sector)*

The agricultural sector of the Campania region can be compared with the national agricultural sector in order to better understand how its performance is related to the local climatic factors (rain, solar irradiation, geothermal heat, soil quality), to the local mix of crops and agronomic practices, and finally how the emergy approach is capable to perceive and express the local variability of performance by means of its very diverse set of indicators.

Table 1.3 and Figure 1.4 show emergy indicators for the whole system of regional agriculture. In Table 1.3 the indicators are respectively calculated with and without

accounting for the emergy that supports labor and services provided to the system. The performance values of the regional agriculture show a relative stability over the investigated period, with small oscillations. The agricultural sector had better indicators in the year 1985, with declining values up to the year 2006 and finally recent improvements back to the value of the 1985 again. The Emergy Yield Ratio declined from 1.16 to 1.10 in 2006, to rise again to 1.16 in 2010, The ELR increased from 7.37 in 1985 up to 11.68 in 2006, to decrease again to 7.39 in 2010.
Similar behavior was shown by the Emergy Sustainability Index (ESI), with values from 0.16 (1985) to 0.09 in 2006 and then 0.16 again in 2010.

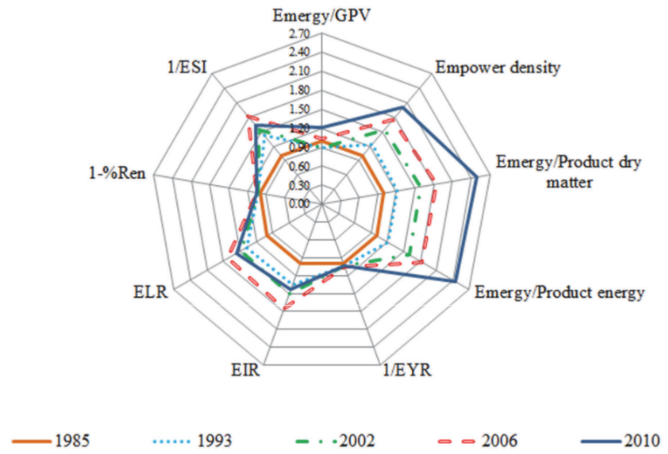


**Figure 1.3** Aggregated diagram of emergy-based environmental performance indicators of the national agricultural sector of Italy. Values in the diagram are normalised according to the first investigated year (chosen as reference). Real values and units are listed in Table 1.2.

*Results from the "n-1" level: selected local farms*

The emergy indicators calculated for lemon, olive and grape farms, underline a higher global environmental impact of the lemon farm compared to the others.
Table 1.4 lists the main emergy indicators for one hectare of the investigated arboriculture calculated for the year 2006. All the indicators are calculated with and without labor and services in order to underline the importance of direct and indirect labor for the products of these particular crops. Moreover, the extensive emergy indicators of renewable input (R), nonrenewable (N), imported (F), direct labor (work force) and indirect labor (cost of all purchased input), are also presented in the Table.

*Discussion*

Results provide a complete and consistent picture of the driving forces supporting the agricultural sector in Italy, thus allowing a better understanding of its performance and main sources of emergy including areas of resource inefficiency. Italian agriculture is

day-by-day more heavily dependent on fossil fuels and other nonrenewable input sources which affects its sustainability to a very large extent.
The comparison of national, regional and local levels does not only aim at suggesting specific variation of cropping practices, but also at testing the ability of the emergy method to properly account for even very specific aspects at local level. A proper set of emergy indicators may become a powerful tool to assess the performance of a production sector trough time and space, thus providing deep insight into the resource use dynamics at multiple scales. Moreover, the comparison of a large number of indicators and case studies also allows simulation of optimization strategies based on selective improvement of one or more input flows or processes.

**Table 1.2** Trends of extensive and intensive emergy indicators of the agricultural system of Italy

| Indicators | Unit | 1985 | 1993 | 2002 | 2006 | 2010 |
|---|---|---|---|---|---|---|
| *Extensive Indicators* | | | | | | |
| Locally renewable inputs, R | seJ/yr | 8.07E+21 | 6.59E+21 | 7.42E+21 | 6.97E+21 | 8.38E+21 |
| Locally nonrenewable inputs, N | seJ/yr | 1.44E+21 | 1.27E+21 | 1.23E+21 | 1.16E+21 | 2.33E+21 |
| Purchased inputs, F | seJ/yr | 3.21E+22 | 3.33E+22 | 2.86E+22 | 2.87E+22 | 4.26E+22 |
| Direct Labor, L, non renewable | seJ/yr | 1.96E+22 | 2.47E+22 | 4.44E+22 | 4.81E+22 | 3.01E+22 |
| Indirect labor (services), non renewable | seJ/yr | 1.46E+22 | 1.64E+22 | 1.78E+22 | 2.23E+22 | 3.49E+22 |
| Total Emergy U= (R+N+F+L+S) | seJ/yr | 7.58E+22 | 8.23E+22 | 9.94E+22 | 1.07E+23 | 1.18E+23 |
| Total Emergy U(*)= (R+N+F) | seJ/yr | 4.16E+22 | 4.12E+22 | 3.73E+22 | 3.68E+22 | 5.33E+22 |
| *Intensive Indicators (with L&S)* | | | | | | |
| Emergy intensity of GPV(**) | seJ/€ | 4.10E+12 | 3.64E+12 | 3.64E+12 | 4.23E+12 | 5.00E+12 |
| Empower density | seJ/ha | 4.46E+15 | 5.50E+15 | 6.85E+15 | 7.83E+15 | 8.89E+15 |
| Emergy intensity per g d.m. | seJ/g | 6.07E+08 | 7.34E+08 | 9.68E+08 | 1.11E+09 | 1.51E+09 |
| Transformity | sej/J | 3.75E+04 | 4.55E+04 | 5.99E+04 | 6.90E+04 | 9.17E+04 |
| EYR = U/(F+L+S) | | 1.14 | 1.11 | 1.10 | 1.08 | 1.10 |
| EIR = 1/(EYR-1) | | 6.97 | 9.48 | 10.49 | 12.19 | 10.04 |
| ELR = (N+F+S)/R | | 8.40 | 11.49 | 12.40 | 14.39 | 13.11 |
| %REN = 1/(1+ELR) | | 0.11 | 0.08 | 0.07 | 0.06 | 0.07 |
| ESI = EYR/ELR | | 0.14 | 0.10 | 0.09 | 0.08 | 0.08 |
| *Intensive Indicators (without L&S)* | | | | | | |
| Emergy intensity of GPV(**) | seJ/€ | 2.25E+12 | 1.82E+12 | 1.37E+12 | 1.45E+12 | 2.25E+12 |
| Empower density | seJ/ha | 2.45E+15 | 2.75E+15 | 2.57E+15 | 2.69E+15 | 4.01E+15 |
| Emergy intensity per g d.m. | seJ/g | 3.33E+08 | 3.67E+08 | 3.63E+08 | 3.83E+08 | 6.81E+08 |
| Transformity | sej/J | 2.06E+04 | 2.27E+04 | 2.25E+04 | 2.37E+04 | 4.14E+04 |
| EYR = U*/F | | 1.30 | 1.24 | 1.30 | 1.28 | 1.25 |
| EIR = 1/(EYR-1) | | 3.37 | 4.24 | 3.31 | 3.53 | 3.98 |
| ELR = (N+F)/L | | 4.15 | 5.25 | 4.02 | 4.29 | 5.36 |
| %REN = 1/(1+ELR) | | 0.19 | 0.16 | 0.20 | 0.19 | 0.16 |
| ESI = EYR/ELR | | 0.31 | 0.24 | 0.32 | 0.30 | 0.23 |

(*) Total emergy without accounting for Labor and Services

(**) GPV = Gross Production Value (€)

*Comparison across Levels: Country-Region-Farm*

A comparison among the performances of the national, regional and local agricultural sectors is provided in Figure 1.5 and Table 1.4, for better understanding of the meaning of the calculated indicators. For the sake of clarity, we refer to a functional unit of one ha of cropped land in the year 2006. Of course, while at the national and regional level such a functional unit refers to an average mix of different crops, at the local level it refers to very specific crops and production practices.

**Table 1.3** Trends of intensive and extensive emergy indicators of the agricultural system of Campania region

| Indicators | Unit | 1985 | 1993 | 2002 | 2006 | 2010 |
|---|---|---|---|---|---|---|
| *Extensive Indicators* | | | | | | |
| Locally renewable inputs, R | seJ/yr | 6.29E+20 | 4.61E+20 | 4.28E+20 | 4.05E+20 | 5.72E+20 |
| Locally nonrenewable inputs, N | seJ/yr | 8.05E+19 | 6.29E+19 | 5.22E+19 | 5.11E+19 | 1.06E+20 |
| Purchased inputs, F | seJ/yr | 1.66E+21 | 1.58E+21 | 1.60E+21 | 1.60E+21 | 1.23E+21 |
| Direct Labor, L, non renewable | seJ/yr | 2.05E+21 | 1.73E+21 | 2.07E+21 | 1.90E+21 | 1.77E+21 |
| Indirect labor (services), non renewable | seJ/yr | 8.49E+20 | 8.43E+20 | 8.80E+20 | 1.17E+21 | 1.13E+21 |
| Total Emergy U= (R+N+F+L+S) | seJ/yr | 5.27E+21 | 4.67E+21 | 5.03E+21 | 5.13E+21 | 4.80E+21 |
| Total Emergy U*= (R+N+F) | seJ/yr | 2.37E+21 | 2.10E+21 | 2.08E+21 | 2.06E+21 | 1.91E+21 |
| *Intensive Indicators with L&S* | | | | | | |
| Emergy intensity of GPV(**) | seJ/€ | 3.44E+12 | 2.72E+12 | 2.04E+12 | 2.31E+12 | 2.10E+12 |
| Empower density | seJ/ha | 5.55E+15 | 6.30E+15 | 8.17E+15 | 8.51E+15 | 7.37E+15 |
| Emergy intensity per g d.m. | seJ/g | 9.92E+08 | 9.00E+08 | 9.52E+08 | 1.01E+09 | 9.84E+08 |
| Transformity | sej/J | 6.22E+04 | 5.53E+04 | 5.89E+04 | 6.42E+04 | 5.86E+04 |
| EYR = U/(F+L+S) | | 1.16 | 1.13 | 1.11 | 1.10 | 1.16 |
| EIR = 1/(EYR-1) | | 6.42 | 7.92 | 9.46 | 10.25 | 6.08 |
| ELR = (N+F+S)/R | | 7.37 | 9.14 | 10.74 | 11.68 | 7.39 |
| %REN = 1/(1+ELR) | | 0.12 | 0.10 | 0.09 | 0.08 | 0.12 |
| ESI = EYR/ELR | | 0.16 | 0.12 | 0.10 | 0.09 | 0.16 |
| *Intensive Indicators without L&S* | | | | | | |
| Emergy intensity of GPV(**) | seJ/€ | 1.55E+12 | 1.22E+12 | 8.46E+11 | 9.27E+11 | 8.34E+11 |
| Empower density | seJ/ha | 2.50E+15 | 2.83E+15 | 3.38E+15 | 3.41E+15 | 2.93E+15 |
| Emergy intensity per g d.m. | seJ/g | 4.47E+08 | 4.05E+08 | 3.94E+08 | 4.04E+08 | 3.91E+08 |
| Transformity | sej/J | 2.80E+04 | 2.48E+04 | 2.44E+04 | 2.58E+04 | 2.33E+04 |
| EYR = U*/F | | 1.43 | 1.33 | 1.30 | 1.28 | 1.55 |
| EIR = 1/(EYR-1) | | 2.34 | 3.01 | 3.33 | 3.52 | 1.81 |
| ELR = (N+F)/L | | 2.77 | 3.56 | 3.86 | 4.09 | 2.33 |
| %REN = 1/(1+ELR) | | 0.27 | 0.22 | 0.21 | 0.20 | 0.30 |
| ESI = EYR/ELR | | 0.51 | 0.37 | 0.34 | 0.31 | 0.67 |

(*) Total emergy without accounting for Labor and Services
(**) GPV = Gross Production Value (€)

Areas in the diagram of Figure 1.5 suggest that the local farms investigated are impacting more than the average national and regional agricultural sectors, on one-hectare basis. This can be explained by the fact that the three investigated farms are very small and do not benefit from any scale factor. Moreover, they are arboricultural farms, requiring more support infrastructure (e.g. the lemon farms require a highly impacting woody structure named "pergolato") and much more care than cereals and forage farms.

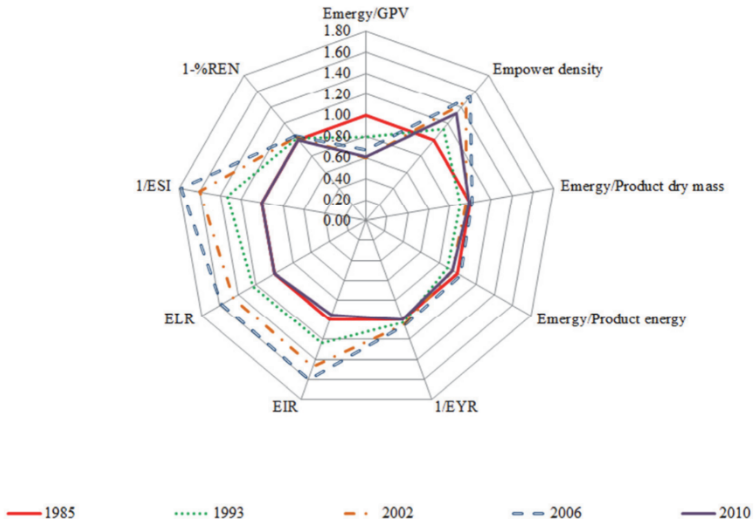


**Figure 1. 4** Aggregated diagram of emergy-based environmental performance indicators of the agricultural sector of Campania region. Values in the diagram are normalised according to the first investigated year (chosen as reference). Real values and units are listed in Table 1.3.

Emergy results for arboricultural farms show a higher demand for environmental support, a higher ELR and a higher reliance on imported resources, than the average values for Italy and Campania region. In particular, if we look at raw values without accounting for labor and services, fertilizers and pesticides (respectively 29% and 23% of total emergy) appear to be very intensively used for olive farm; energy consumption (24%) and fertilization (28%) also affect the wineyard performance, while infrastructure is crucial for lemon farming (44%) due to the need for the "pergolato" shading structure. The latter is characterized by the use of a woody and galvanized steel support infrastructure, that is economically expensive and emergy intensive (although allocated to 30 life-time years and partially recycled).

While the comparison between regional and national level points out (Tables 1.2 and 1.3) that the Italian agriculture as a whole is more emergy intensive than Campania regional agriculture. The Environmental Loading Ratio (ELR) in the year 1985 was 7.37 for Campania agriculture, while it was 8.40 for the Italian agricultural sector. From 1985 to 2010 the regional ELR increased till the year 2006 and then decreased back to the 1985 value; instead, the ELR of Italian agriculture increased by 56% in the same years, from 8.40 (1985) to 13.11 (2010). The Emergy Yield Ratio (EYR) of Italian agriculture decreased from 1.14 (1985) to 1.10 (2010), while it decreased from 1.16 (1985) to 1.10 (2006) to increase again to 1.16 (2010) at the regional level. The two parameters combined together generated an Emergy Sustainability Index (ESI) that is higher for the Campania region (0.16 in 2010) than for Italy (0.08 in the same year).

At the farm level, results are of course affected by local specificity in resource use, management, environmental conditions and individual crops. The three case studies investigated in the year 2006 (lemon, olive and grape farms) show the same values of the EYR (1.02), while their ELRs were equal to 62.11, 56.02, and 50.69 respectively, all much higher than for the average agricultural national and regional sectors.

Intensity indicators are relatively independent on the physical size, and provide a measure of efficiency or performance of the agricultural production at different scale (e.g., more or less material or energy used per unit of product or per unit of time). The calculated values (emergy/GPV, emergy/land; emergy/product mass; emergy/product energy) suggest a higher efficiency for the two "average hectares" of regional and national scales compared to the local farms (Table 1.4), by also pointing out that the regional sector is more efficient than the national one.

**Table 1.4** Emergy indicators per hectare of the agricultural sectors of Italy and Campania region compared to three local farms in the same region (data refer to the year 2006)

| Indicators | Unit | Italy | Campania | Lemon | Olive | Grape |
|---|---|---|---|---|---|---|
| ***Extensive Indicators*** | | | | | | |
| Locally renewable inputs, R | seJ/yr | 5.09E+14 | 5.49E+14 | 6.18E+14 | 4.52E+14 | 5.79E+14 |
| Locally nonrenewable inputs, N | seJ/yr | 8.48E+13 | 8.48E+13 | 8.48E+13 | 8.48E+13 | 8.48E+13 |
| Purchased inputs, F | seJ/yr | 2.10E+15 | 2.66E+15 | 7.56E+15 | 2.52E+15 | 2.75E+15 |
| Direct Labor, L, non renewable | seJ/yr | 3.51E+15 | 3.69E+15 | 1.92E+16 | 1.80E+16 | 2.20E+16 |
| Indirect labor (services), non | seJ/yr | 1.63E+15 | 1.94E+15 | 1.15E+16 | 3.65E+15 | 4.49E+15 |
| Total Emergy U= (R+N+F+L+S) | seJ/yr | 7.83E+15 | 8.93E+15 | 3.90E+16 | 2.47E+16 | 2.99E+16 |
| Total Emergy $U^{(*)}$= (R+N+F) | seJ/yr | 2.69E+15 | 3.29E+15 | 8.27E+15 | 3.05E+15 | 3.41E+15 |
| ***Intensive Indicators with L&S*** | | | | | | |
| Emergy intensity of $GPV^{(**)}$ | seJ/€ | 4.23E+12 | 2.31E+12 | 2.36E+12 | 7.36E+12 | 8.31E+12 |
| Empower density | seJ/ha | 7.83E+15 | 8.51E+15 | 3.90E+16 | 2.47E+16 | 3.41E+15 |
| Emergy intensity per g d.m. | seJ/g | 1.11E+09 | 1.01E+09 | 1.24E+10 | 1.11E+10 | 1.01E+10 |
| Transformity | seJ/J | 6.90E+04 | 6.42E+04 | 2.83E+06 | 4.34E+05 | 7.73E+05 |
| EYR = U/(F+L+S) | | 1.08 | 1.10 | 1.02 | 1.02 | 1.02 |
| EIR = 1/(EYR-1) | | 12.19 | 10.25 | 54.49 | 47.01 | 44.09 |
| ELR = (N+F+S)/R | | 14.39 | 11.68 | 62.11 | 56.02 | 50.69 |
| %REN = 1/(1+ELR) | | 0.06 | 0.08 | 0.02 | 0.02 | 0.02 |
| ESI = EYR/ELR | | 0.08 | 0.09 | 0.02 | 0.02 | 0.02 |
| ***Intensive Indicators without L&S*** | | | | | | |
| Emergy intensity of $GPV^{(**)}$ | seJ/€ | 1.45E+12 | 9.27E+11 | 5.01E+11 | 8.72E+11 | 9.48E+11 |
| Empower density | seJ/ha | 2.69E+15 | 3.41E+15 | 8.27E+15 | 3.05E+15 | 3.41E+15 |
| Emergy intensity per g d.m. | seJ/g | 3.83E+08 | 4.04E+08 | 2.62E+09 | 1.32E+09 | 1.15E+09 |
| Transformity | seJ/J | 2.37E+04 | 2.58E+04 | 5.99E+05 | 5.14E+04 | 8.82E+04 |
| EYR = U*/F | | 1.28 | 1.28 | 1.09 | 1.21 | 1.24 |
| EIR = 1/(EYR-1) | | 3.53 | 3.52 | 10.77 | 4.69 | 4.14 |
| ELR = (N+F)/L | | 4.29 | 4.09 | 12.38 | 5.75 | 4.89 |

| | | | | | |
|---|---|---|---|---|---|
| %REN = 1/(1+ELR) | 0.19 | 0.20 | 0.07 | 0.15 | 0.17 |
| ESI = EYR/ELR | 0.30 | 0.31 | 0.09 | 0.21 | 0.25 |

(*) Total emergy without accounting for Labor and Services

(**) GPV = Gross Production Value (€)

All the values above include the emergy supporting labor and services (L&S) in the process. If L&S are not included, variations in the range 30% 50% are calculated, as a consequence of the special laborintensive structure of Italian and regional agricultural sectors.

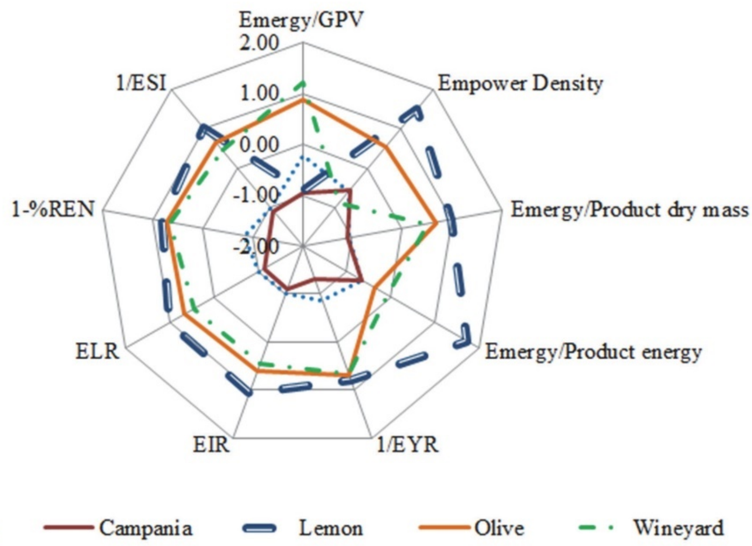


**Figure 1.5** Comparison of the performance indicators of national, regional and local scale agricultural systems in the year 2006. Values in the diagram are normalised according to the standard score normalization. Real values and units are listed in Table 1.4.

## Scenario Analysis

In order to evaluate strategies and scenarios for innovative patterns in agriculture, selected opportunities and alternatives are explored by making use the most crucial parameters (e.g. fertilizers, machinery and fuels). In this study a scenario analysis was performed in the case of Campania Region agriculture by assuming percent changes of direct input flows (e.g. more or less nitrogen fertilizer) and indirect input flows (e.g. more or less efficient industrial production of nitrogen fertilizer, translating into a lower or higher emergy intensity value), in order to explore the consequences of efficiency changes on calculated indicators. Assumptions are related to specific policy or technical actions applied to the situation of the year 2006 as the starting point:

a) decreased amount of input flows due to more efficient use (e.g. more accurate spread of fertilizers, better irrigation devices; good maintenance of machinery for fuel conservation and longer lasting);
b) increased use of renewable sources of energy and materials (e.g. solar modules for water heating; photovoltaic electricity; woody structures; etc) instead of fossil fuels, iron and concrete;

c) replacement of input flows by means of co-products of the process (e.g. less energy input and more use of biogas from anaerobic digestion of residues from agriculture or food industry; less nitrogen and more fertilizer from composting of residues; etc);
d) improvement of the technical performance of the upstream production chain, in order to decrease the material, energy and emergy production costs of the input flows (e.g. different production patterns; technological innovation; conservation measures applied to the production chain; etc);
e) increased output, thanks to the production and market valorization of value-added products (chemicals, bioenergy, biomaterials, cosmetics, fibers, food integrators, etc) that increase the output (GDP, energy content, mass) and affect the performance indicators per unit of output.

It clearly appears that the choices in points (a) to (e) above translate into variations of input and output flows or intensities in scenario analysis, that in turn translate into quantified changes of the impacts. The input flows to Campania regional agriculture, responsible for the largest environmental impact, were identified from a reference scenario (Scenario A, business as usual): diesel, machinery, fertilizers (nitrogen) and labor. The application of scenario analysis consisted in selected variations of such input flows by assuming selected percentages of change: -20% of diesel, machinery and nitrogen input flows; -50% of electricity input and, from -10% to -20% of the emergy intensities. Of course, the decrease of purchased inputs also entails a decrease of the related services.
Results obtained from the combination of the above changes are shown in the radar diagram of Figure 1.6, according to the following scenarios:

- Scenario A: business as usual;
- Scenario B: -20% of diesel, machinery and nitrogen input flows;
- Scenario C: -20% of diesel, machinery and nitrogen emergy intensities;
- Scenario D: -10% of diesel, machinery and nitrogen emergy intensities, -50% of electricity intensities, -10% of diesel, machinery and nitrogen input flows;
- Scenario E: -20% of diesel, machinery and nitrogen emergy intensities, -50% of electricity emergy intensity, -20% of diesel, machinery and nitrogen input flows.

Variations of performance indicators are assumed to be generated by an improvement of technologies (agricultural machinery as well as improved production chains of input flows used) or by a more efficient use of local resources, in order not to alter the final agricultural production. The scenario results applied to the performance indicators of regional agriculture in the year 2010 suggest that non-negligible improvements can be achieved (scenario E versus Scenario A-Business as Usual) by improving the efficiency of supply and use process chains by small percentages, without affecting the final yield. Reuse of residues for energy, implementation of solar thermal and photovoltaic energy, replacement of conventional irrigation by means of drip irrigation, increase of machinery efficiency are likely to provide much better opportunities for energy and material resource savings, thus increasing the overall sustainability.

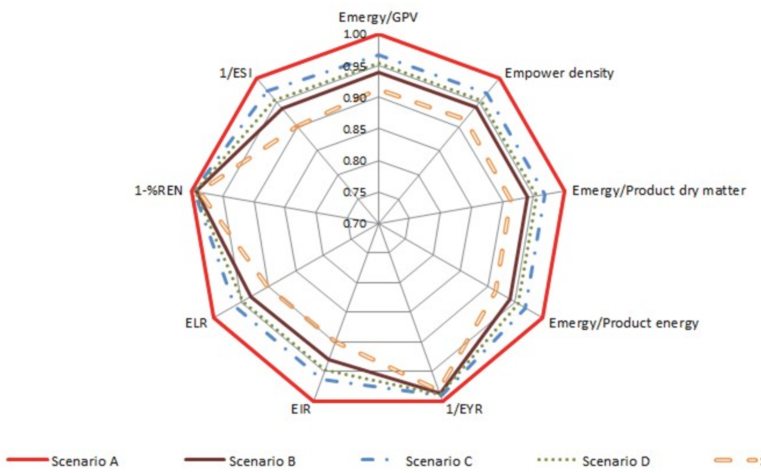


**Figure 1.6** Emergy indicators calculated for different scenarios in Campania region (reference year: 2010). Values in the diagram are normalised with reference to scenario A (business as usual). Real values and units are listed in Table 1.5.

**Table 1.5** Indicators of environmental performance and sustainability of Campania region agriculture, calculated under five different scenario assumptions(*)

| Indicators (with L&S) | Unit | Scenario A | Scenario B | Scenario C | Scenario D | Scenario E |
|---|---|---|---|---|---|---|
| Emergy/GPV(§) | seJ €$^{-1}$ | 8.34E+11 | 7.63E+11 | 7.66E+11 | 7.66E+11 | 7.07E+11 |
| Empower density | seJ ha$^{-1}$ yr$^{-1}$ | 2.93E+15 | 2.68E+15 | 2.69E+15 | 2.69E+15 | 2.48E+15 |
| Emergy/Yield Mass (d.m.) | seJg$^{-1}$ | 9.84E+08 | 9.26E+08 | 9.53E+08 | 9.40E+08 | 8.99E+08 |
| Transformity | seJ J$^{-1}$ | 5.86E+04 | 5.51E+04 | 5.67E+04 | 5.60E+04 | 5.36E+04 |
| EYR | | 1.16 | 1.18 | 1.18 | 1.18 | 1.18 |
| EIR | | 6.08 | 5.66 | 5.85 | 5.76 | 5.47 |
| ELR | | 7.39 | 6.89 | 7.12 | 7.01 | 6.67 |
| %REN | | 0.12 | 0.13 | 0.12 | 0.12 | 0.13 |
| ESI | | 0.16 | 0.17 | 0.16 | 0.17 | 0.18 |

(*) Reference year: 2010. Scenario A (business as usual); Scenario B (decrease by 20% of diesel, machinery and nitrogen input flows); Scenario C (decrease by 20% of diesel, machinery and nitrogen emergy intensities); Scenario D (decrease by 10% of diesel, machinery and nitrogen emergy intensities, decrease by 50% of electricity intensities, decrease by 10% of diesel, machinery and nitrogen input flows); Scenario E: (decrease by 20% of diesel, machinery and nitrogen emergy intensities, decrease by 50% of electricity emergy intensity, decrease by 20% of diesel, machinery and nitrogen input flows).

(§) GPV= Gross Production Value

**Preliminary conclusions**

Three different hierarchical levels of Italian agriculture were investigated and their performances across scales quantitatively assessed. The decreasing renewability of the agricultural sector and the main factors of its unsustainability and resilience (ability to face perturbations in the surrounding environment, in order to decrease vulnerability: e.g. increased oil scarcity) were pointed out. The application of the emergy method was proved to be an effective tool to quantify the development potential achievable as a consequence of efficiency or technological improvement.

In order to generate a clear picture of the investigated system it was fundamental to identify the crucial steps and the main input and output flows, i.e. those steps and those flows that affected more heavily the process performance. In so doing it was possible to focus on them in order to understand their importance to the global dynamics of the investigated process, suggest changes capable of improving performance and draw scenarios of systems' response to oscillations of production factors.

The emergy approach and the related scenario analysis allow to investigate if and how some steps might be replaced by alternative patterns, some input flows be decreased by means of more efficient machinery or sub-processes, and finally some input flows simply be avoided without any important consequence for the final product. Therefore, when a calculated performance indicator is not satisfactory, the analyst can go back to the calculation procedure in order to identify the input items that are more responsible for a performance drop and may suggest to decrease their amount by applying more efficient resource use and technological changes to the process (e.g., use of a different source of energy or crop rotation or decreased amount of fertilizer or recycling patterns). After the suggested changes are implemented (or their adoption simulated), the analyst is able to recalculate the unsatisfactory indicator and assess the potential for performance improvement.

The whole assessment procedure was made possible, at all scales, by the use of the emergy synthesis approach. The latter proved to be capable of combining:

i. different kinds of renewable and nonrenewable as well as local and imported input flows (fertilizers, fuels, machinery and so on, including the emergy associated to labor and services);
ii. different production strategies;
iii. spatial and time scales; and finally
iv. planned or undesired time oscillations of combined sets of parameters,

and generate performance indicators, evaluations of past trends, and design of scenarios for sound agricultural policy making.

## *B. Comparison with Scottish agriculture*

The performances of national Italian and Scottish agricultural systems were investigated over time (1985, 1993, 2002, 2006 and 2010 for the Italian system; 1991, 2001, 2007 and 2010 for the Scottish one). Land cover and land use of these countries are shown in Figure 1.7, with large fractions of intensive agriculture in Italy and large fractions of semi-natural and natural landscape in Scotland. Of course, the two systems are also characterized by very different climate, temperature and cropping systems.

*The investigated system(s)*

High soil fertility, good climate conditions and water abundance characterize the Italian agriculture, thus enabling the production of a large variety of high-quality fruit and vegetable products. The agricultural sector in Italy is still a very important economic, environmental and social activity in support of a large fraction of population directly involved in agricultural production and agro-industrial food manufacture. Nevertheless, the Italian agricultural sector is far from reaching a high share of the Italian GDP (in the year 2010 agricultural GDP was only 6% of the national GDP) [ISTAT, 2012]. The northern part of Italy produces primarily grains, sugar beets, soybeans, meat, and dairy products, while the southern part is specialized in fruits, vegetables, olive oil, wine, and durum wheat.

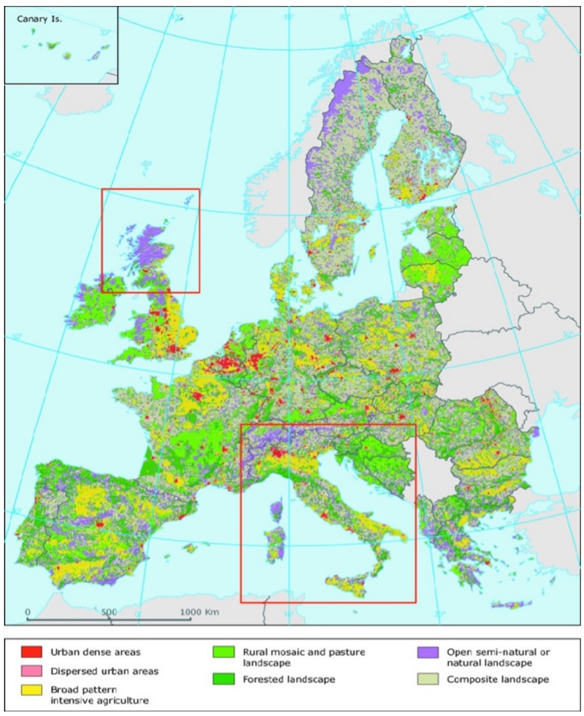


**Figure 1.7** Investigated systems in dominant landscape types of Europe. Source: Corine land cover 2010 (and-maps/data/corine-land-cover-2006-raster).

Scotland, located in the north of Britain, is very well known for its mountainous landscape rich with forests, rivers, and lakes. Scottish landscape makes difficult to carry out productive activities: the European Union acknowledges the existence of natural and geographic disadvantages and, as a consequence of this problem, 85% of Scotland's land is considered "Less Favoured Area". Agriculture is one of the most important economic activities carried in this country; the 94% of total land of Scotland is defined rural by the Scottish government (http://www.scotland.gov.uk/Publications/2010/08/2010UR), about 65,000 people are directly employed in agriculture and it is estimated that more or less 250,000 jobs (1 out of 10 of all Scottish jobs) derive from this sector.

A generic system diagram of an agricultural system is shown in Figure 1.8. The renewable sources (sun, rain, wind and deep heat) are shown in the left side of the diagram. These sources go directly and indirectly in support of the whole investigated system. In addition to renewable flows, further imported flows from the main economy (fertilizers, pesticides, fossil fuels, electricity, goods, machinery and labor) support agricultural production. These flows are shown as entering from the top of the system diagram. The "assets" symbol represents in aggregate form the most typical infrastructures of agricultural systems (barns, storage buildings, irrigation system, etc).
Agricultural products are exported and market pays for them. Such money adds up to the total budget of the agricultural sector, indicated in the diagram as money storage. The agricultural budget is mainly composed by the money that farm workers receive as an income of productive activities (products sold), as well as contribution from external investments. Money is then used to pay for the resources imported in support to the system.

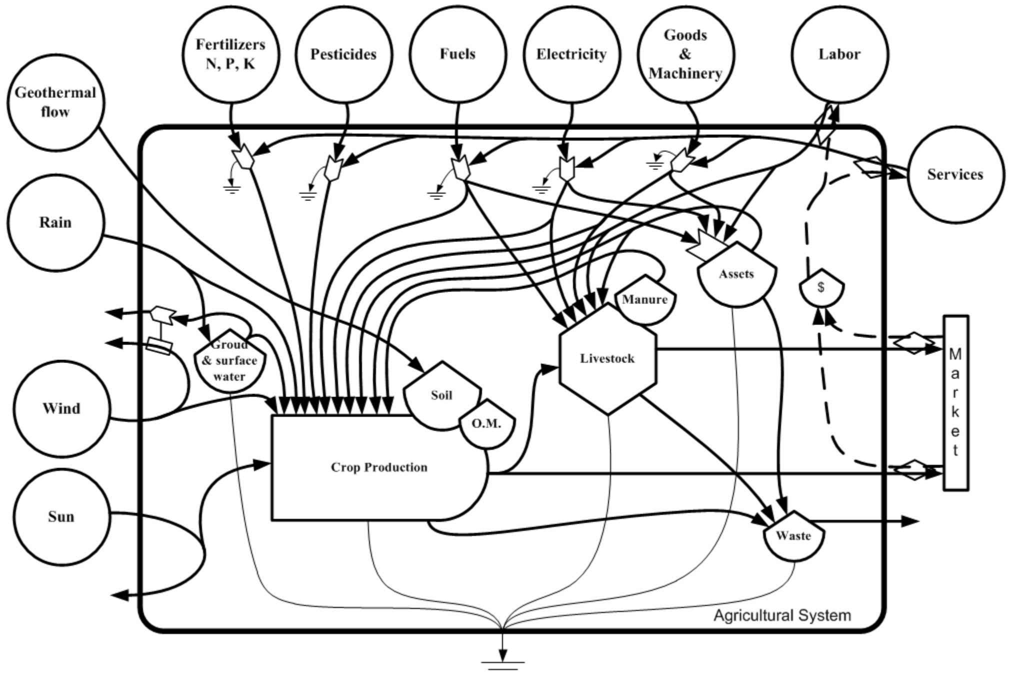


**Figure 1.8** System diagram for a generic agricultural and livestock system.

*Calculation procedure*

Based on the systems diagram of Figure 1.8, tables of input and output flows were constructed for the two investigated systems (Italian and Scottish agricultures). All data were collected, on a yearly basis, in order to account for the supporting matter, energy and money flows. Firstly, an inventory of all the input and output flows is generated, on the local scale of the system. This inventory forms the common basis for all subsequent impact assessments, which are carried out in parallel, thus ensuring the maximum consistency of the input data and inherent assumptions. The raw amounts of input and output flows from the inventory phase are multiplied by suitable conversion coefficients specific of each method previously described, which express the "intensity" of the flow, i.e. quantify to what extent cumulative material, energy, or environmental costs are associated to each flow over its whole life cycle. Such coefficients are available in life cycle assessment, energy and environmental accounting literature. Material, energy, and environmental "costs" associated to each flow are calculated, according to the following generic Equation (4):

$$C = \sum C_i = \sum f_i \times c_i \qquad (4)$$

where $C$ = material, energy or environmental cost associated to the investigated process, i.e. cumulative matter, energy, emergy and emissions associated to that process on the biosphere scale; $C_i$ = material, energy or environmental cost associated to the $i$th inflow or outflow of matter or energy; $f_i$ = raw amount of the $i$th flow of matter, energy, labor; $c_i$ = material, energy or environmental unit cost coefficient of the $i$th flow (from literature or calculated in this work). The material, energy or environmental cost $C$ is finally divided by the process product $p$ (in our case the dry mass, money value and energy content of Italian and Scottish agricultural yields), in order to generate production cost indicators according to the method applied. A large set of performance indicators can also be calculated, e.g. EROI in energy analysis, and EYR, ELR, ESI among others in emergy analysis. The calculated indicators are then interpreted within a comparative procedure, in which the results of each method are set up against each other and contribute to a comprehensive picture, on which scientific and policy conclusions can be drawn. The livestock sector is not included in the present study, but agricultural production of forage and other livestock feedstock do.

**Results**

*Performance of the Italian agricultural sector*

Based on the energy system diagram (Figure 1.8), an inventory of input and output flows was constructed for each investigated year [ISTAT, 1985, 1993, 2001, 2006, 2012] to evaluate the agricultural trend over a 25 year time-frame (Table 1.6). In the investigated period, land cropped decreased, and so did fertilizers and pesticides, while electricity, liquid fuels and machinery increased. Direct labor decreased in terms of hours applied, but its money cost increased, together with the cost of services. The mass and energy content of agricultural yield decreased, while instead the current price economic value increased although with some fluctuations. Inventory data were then converted into cumulative material demand, cumulative energy demand, environmental support, and emissions, to generate performance indicators over time. The main calculated indicators are listed in Table 1.7 as: abiotic material intensity ($MI_{abiot}$) and water intensity ($MI_{water}$) (i.e., abiotic matter and water degraded in all the steps of the process); energy intensities (cumulative commercial energy demand expresses as joule or oil equivalent, $g_{oil\ eq.}$); emergy intensities (demand for global environmental support to the process); airborne and waterborne emission intensities (according to selected LCA impact categories). Indicators are calculated in relation to selected functional units (dry mass produced, energy made available in the product; economic value of the yield; hectares of cropped land). For example, according to Table 1.7, one euro of GDP generated by the agricultural production required in the year 2010 about 3 kg of abiotic matter, 100 m3 of water, 11 MJ of energy (translating into 263 grams of oil equivalent), 5.00E+12 seJ of environmental support, and finally generated a global warming contribution of 827 g of CO2-equivalent.

A selection of indicators from Table 1.7 is graphically shown in the radar diagram of Figure 1.9. To compare data with different orders of magnitude in the same radar diagram, a normalization procedure was applied (all values divided by the value of the first year of investigation) so that a larger area suggests a higher relative impact.

**Table 1.6** Direct supply, land use and product generated: Agricultural sector in Italy.

| Flows | Unit | 1985 | 1993 | 2002 | 2006 | 2010 |
|---|---|---|---|---|---|---|
| Rainfall | g/yr | 1.19E+17 | 9.71E+16 | 1.09E+17 | 1.03E+17 | 1.01E+17 |
| Total land | ha/yr | 1.70E+07 | 1.50E+07 | 1.45E+07 | 1.37E+07 | 1.33E+07 |
| Fertilizers ($N + PO_4 + K_2O$) | g/yr | 1.96E+12 | 1.98E+12 | 1.60E+12 | 1.48E+12 | 1.01E+12 |
| Nitrogen (N) | g/yr | 1.01E+12 | 9.45E+11 | 8.51E+11 | 8.27E+11 | 5.41E+11 |
| Phosphate ($P_2O_5$) | g/yr | 6.10E+11 | 6.39E+11 | 4.27E+11 | 3.61E+11 | 2.43E+11 |
| Potassium ($K_2O$) | g/yr | 3.40E+11 | 3.91E+11 | 3.19E+11 | 2.94E+11 | 2.21E+11 |
| Pesticides | g/yr | 1.20E+11 | 1.29E+11 | 1.55E+11 | 1.14E+11 | 6.11E+10 |
| Electricity | J/yr | 1.18E+16 | 1.66E+16 | 1.76E+16 | 1.98E+16 | 2.02E+16 |
| Water for irrigation | g/yr | 7.89E+15 | 4.64E+15 | 3.41E+15 | 2.35E+15 | 2.00E+16 |
| Liquid fuels | J/yr | 7.92E+16 | 1.04E+17 | 8.46E+16 | 9.60E+16 | 9.75E+16 |
| Machinery | kg/yr | 2.58E+08 | 2.32E+08 | 2.25E+08 | 2.17E+08 | 5.02E+08 |
| Direct labor | hours/yr | 2.19E+09 | 2.00E+09 | 1.88E+09 | 1.75E+09 | 1.16E+09 |
| Direct labor | €/yr | 4.58E+09 | 8.31E+09 | 1.61E+10 | 1.75E+10 | 1.09E+10 |
| Indirect labor (services) | €/yr | 3.43E+09 | 5.54E+09 | 6.46E+09 | 8.11E+09 | 1.27E+10 |
| **Products** | | | | | | |
| Mass of agricultural production | g dry matter/yr | 1.25E+14 | 1.12E+14 | 1.03E+14 | 9.63E+13 | 7.84E+13 |
| Energy content of agricultural | J/yr | 2.02E+18 | 1.81E+18 | 1.66E+18 | 1.55E+18 | 1.29E+18 |
| Economic value of agricultural | €/yr | 1.85E+10 | 2.26E+10 | 2.73E+10 | 2.53E+10 | 2.37E+10 |

Increasing areas in the diagram clearly point out that the Italian agriculture is becoming less sustainable and is day-by-day turning into a fossil fuel based economy. This is affecting its ability to serve as a source of renewable materials, food, energy and ecosystem services (e.g. water holding ability and stabilization of organic matter in soil). The decreasing performance is affected by a mix of factors: large rainfall oscillations and related variation of irrigation practices, decreased amount of arable land, variation of the mix of crops, change in technology (increased agricultural machinery use), decrease of labor, increased use of fertilizers and other chemicals. Such variations of input values translate into important changes of the performance indicators that in turn globally translate into a different shape and area of the radar diagrams.

*Performance of the Scottish agricultural sector*

The inventory data of the Scottish agricultural sector (Table 1.8, [Yeates and Simpson, 2010; Viglia et al, 2011; SAS, 2013]) show increasing cropped land, decreasing use of fertilizers and pesticides (with some fluctuation), decreasing electricity, increasing fuels and machinery. Labor increases both in terms of hours invested and money cost. Instead, services show a relatively constant trend. The mass of agricultural production increases and so do its energy content and economic value. The declining £/€ exchange rate between euro and sterling partially hides the constant increase of economic value when expressed in Euro (in 2007, 1 £ was equivalent to 1.467 € while instead in 2010 it was only valued 1.167 €).

Table 1.8 lists the main indicators obtained in this study. The indicators are the same as in Table 1.7 for Italy, in order to ease comparison.

A pictorial overview of selected results is provided in Figure 1.10 showing oscillating performances around the reference year 1991. It should be noted that the radar diagram was generated by only using intensive indicators, not extensive ones, so that the diagram's behavior is not dependent on the different physical area of the system in the investigated years. The possibility to compare selected impact categories of investigated systems (e.g. energy depletion, demand for environmental support, contribution to global warming, acidification, eutrophication) is an important aspect of the approach specially if the assessment aims at process improvement, resource use policy making or finally large scale development planning. Much more important is that the calculation procedure applied to this study allows to identify what are the categories that are responsible of the largest impacts and, within each category, what is the process step that generates the highest loading; finally, it can be seen, within each step, what is the item to be charged for the heaviest contribution and therefore needing improvement effort. Comparison can be made between the present process performance and performances in previous years over a time series, between two processes yielding the same product or service, and finally between scenarios based on improvement assumptions.

In the present study we focus on two very different agricultural systems. The case studies show the way the assessment approach is applied and highlight its potentialities for further application to agricultural systems at all scales.

**Table 1.7.** Performance of the Italian agricultural sector in selected years.

| | 1985 | 1993 | 2002 | 2006 | 2010 |
|---|---|---|---|---|---|
| **Material resource depletion** | | | | | |
| $MI_{abiot}$ (g/g d.m.) | 0.55 | 0.61 | 0.60 | 0.63 | 0.91 |
| $MI_{abiot}$ (g/€) | 3.69E+03 | 3.02E+03 | 2.27E+03 | 2.39E+03 | 3.01E+03 |
| $MI_{abiot}$ (g/J) | 3.39E-05 | 3.77E-05 | 3.74E-05 | 3.90E-05 | 5.52E-05 |
| $MI_{abiot}$ (g/ha) | 4.02E+06 | 4.56E+06 | 4.28E+06 | 4.43E+06 | 5.35E+06 |
| $MI_{water}$ (g/g d.m.) | 65.56 | 44.48 | 36.37 | 27.92 | 29.47 |
| $MI_{water}$ (g/€) | 4.43E+05 | 2.21E+05 | 1.37E+05 | 1.06E+05 | 9.76E+04 |
| $MI_{water}$ (g/J) | 4.06E-03 | 2.75E-03 | 2.25E-03 | 1.73E-03 | 1.79E-03 |
| $MI_{water}$ (g/ha) | 4.82E+08 | 3.33E+08 | 2.57E+08 | 1.96E+08 | 1.74E+08 |
| Total abiotic material requirement | 6.83E+13 | 6.82E+13 | 6.21E+13 | 6.07E+13 | 7.12E+13 |
| Total water Footprint | 8.19E+15 | 4.98E+15 | 3.73E+15 | 2.69E+15 | 2.03E+16 |
| Global to Local Abiotic | 2.24 | 2.44 | 2.35 | 2.40 | 1.52 |
| Global to Local Water | 1.04 | 1.07 | 1.09 | 1.14 | 1.02 |
| **Energy resource depletion** | | | | | |
| GER per unit of mass (J/g d.m.) | 2.21E+03 | 2.63E+03 | 2.52E+03 | 2.76E+03 | 3.33E+03 |
| GER per unit currency (J/€) | 1.49E+07 | 1.30E+07 | 9.47E+06 | 1.05E+07 | 1.10E+07 |
| GER per unit of energy (J/J) | 0.14 | 0.16 | 0.16 | 0.17 | 0.20 |
| GER per ha (J/ha) | 1.63E+10 | 1.97E+10 | 1.78E+10 | 1.94E+10 | 1.96E+10 |
| Oil eq. (g/g d.m.) | 0.05 | 0.06 | 0.06 | 0.07 | 0.08 |
| Oil eq. (g/€) | 3.57E+02 | 3.11E+02 | 2.26E+02 | 2.50E+02 | 2.63E+02 |
| Oil eq. (g/J) | 3.27E-06 | 3.89E-06 | 3.72E-06 | 4.08E-06 | 4.83E-06 |
| Oil eq. (g/ha) | 3.88E+05 | 4.71E+05 | 4.26E+05 | 4.63E+05 | 4.68E+05 |
| EROI (Energy of products/Total embodied energy applied) | 7.30 | 6.15 | 6.42 | 5.86 | 6.91 |
| Global to Local Energy | 3.04 | 2.45 | 2.53 | 2.29 | 3.06 |
| **Emergy, demand for environmental support** | | | | | |
| Specific emergy (with L&S) (seJ/g d.m.) | 3.33E+08 | 3.67E+08 | 3.63E+08 | 3.83E+08 | 6.81E+08 |
| Specific emergy (with L&S) (seJ/€) | 4.10E+12 | 3.64E+12 | 3.64E+12 | 4.23E+12 | 5.00E+12 |
| Transformity (with L&S) (seJ/J) | 3.75E+04 | 4.55E+04 | 5.99E+04 | 6.90E+04 | 9.17E+04 |
| Empower density (with L&S) (seJ/ha) | 4.46E+15 | 5.50E+15 | 6.85E+15 | 7.83E+15 | 8.89E+15 |
| Emergy Yield Ratio (with L&S) = U/(F+L+S) | 1.14 | 1.11 | 1.10 | 1.08 | 1.10 |
| Environmental Loading Ratio (with L&S) = (N+F+L+S)/(R) | 8.40 | 11.49 | 12.40 | 14.39 | 13.11 |
| Environmental Sustainability Index (with L&S) = EYR/ELR | 0.14 | 0.10 | 0.09 | 0.08 | 0.08 |
| **Climate change** | | | | | |
| Global warming (Carbon footprint; $CO_2$-eq., g/g d.m.) | 0.17 | 0.20 | 0.18 | 0.20 | 0.25 |
| Global warming (Carbon footprint; $CO_2$-eq., g/€) | 1.16E+03 | 9.87E+02 | 6.92E+02 | 7.60E+02 | 8.27E+02 |
| Acidification ($SO_2$-eq., g/g d.m.) | 5.82E-04 | 7.39E-04 | 1.17E-03 | 1.22E-03 | 7.43E-04 |
| Acidification ($SO_2$-eq., g/€) | 3.93 | 3.67 | 4.40 | 4.62 | 2.46 |
| Eutrophication ($PO_4$-eq., g/g d.m) | 6.98E-05 | 1.01E-04 | 7.09E-05 | 7.77E-05 | 9.99E-05 |
| Eutrophication ($PO_4$-eq., g/€) | 4.71E-01 | 5.02E-01 | 2.67E-01 | 2.95E-01 | 3.31E-01 |

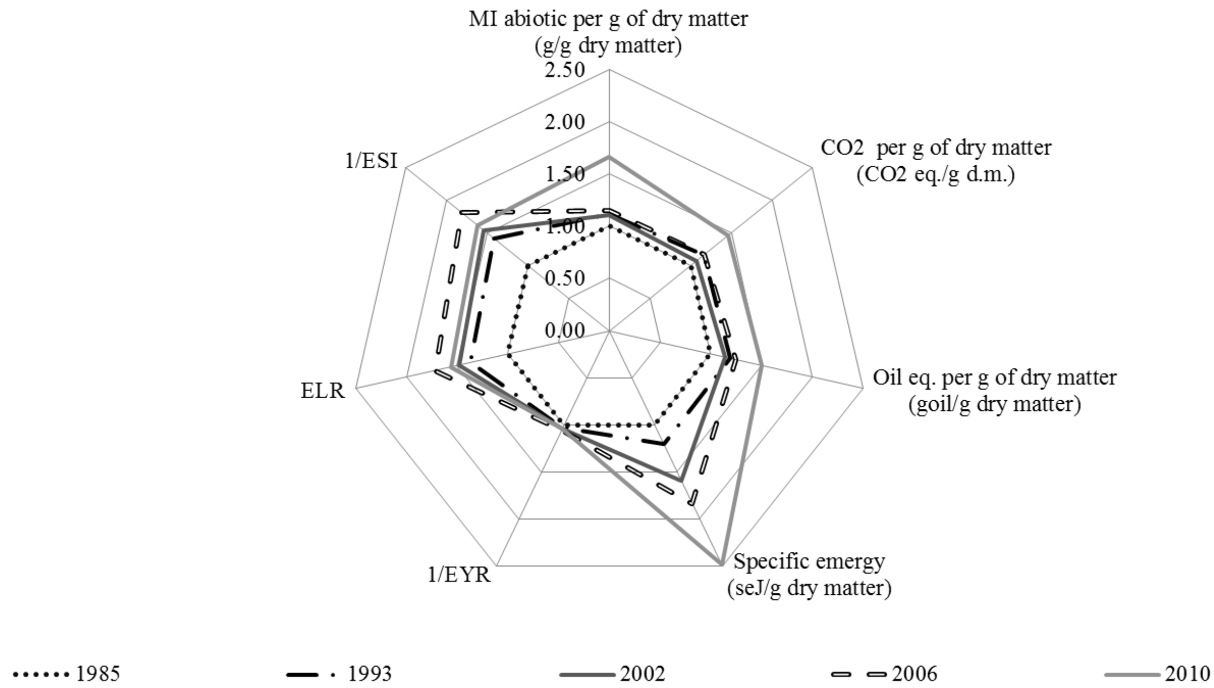


**Fig. 1.9** The radar diagram shows the performance indicators of Italian agriculture over time. Values normalized from Table 1.7.

**Table 1.8.** Direct supply, land use and product generated within the agricultural sector in Scotland

| Flows | Unit | 1991 | 2001 | 2007 | 2010 |
|---|---|---|---|---|---|
| Rainfall | g/yr | 2.48E+16 | 2.44E+16 | 2.71E+16 | 2.45E+16 |
| Total land | ha/yr | 1.77E+06 | 1.87E+06 | 1.84E+06 | 1.95E+06 |
| Fertilizers (N+ PO4 +K2O), TOTAL | g/yr | 3.28E+11 | 4.02E+11 | 2.48E+11 | 2.80E+11 |
| Nitrogen (N) | g/yr | 1.95E+11 | 2.27E+11 | 1.38E+11 | 1.64E+11 |
| Phosphate | g/yr | 6.13E+10 | 8.10E+10 | 4.90E+10 | 4.96E+10 |
| Potassium (K2O) | g/yr | 7.17E+10 | 9.40E+10 | 6.10E+10 | 6.66E+10 |
| Pesticides | g/yr | 2.09E+09 | 1.44E+09 | 1.43E+09 | 9.98E+08 |
| Growth regulators, molluscicides and | g/yr | 4.63E+08 | 4.63E+08 | 2.01E+08 | 1.41E+08 |
| Electricity | J/yr | 3.22E+14 | 2.09E+14 | 2.42E+14 | 2.60E+14 |
| Water for irrigation | g/yr | 5.23E+12 | 5.23E+12 | 5.23E+12 | 5.23E+12 |
| Liquid fuels | J/yr | 3.95E+15 | 4.34E+15 | 5.59E+15 | 5.99E+15 |
| Machinery | g/yr | 1.09E+11 | 1.48E+11 | 4.05E+11 | 4.34E+11 |
| Direct labor | hours/yr | 3.04E+07 | 3.58E+07 | 4.76E+07 | 4.66E+07 |
| Direct labor | €/yr | 2.01E+08 | 3.61E+08 | 5.26E+08 | 6.06E+08 |
| Direct labor | £/yr | 1.32E+08 | 2.24E+08 | 3.59E+08 | 5.19E+08 |
| Indirect labor (services) | €/yr | 1.25E+09 | 1.28E+09 | 1.09E+09 | 1.04E+09 |
| Indirect labor (services) | £/yr | 8.23E+08 | 7.97E+08 | 7.46E+08 | 8.89E+08 |
| **Products** | | | | | |
| Economic value of agricultural production | €/yr | 1.48E+09 | 2.15E+09 | 2.68E+09 | 2.22E+09 |

| | | | | | |
|---|---|---|---|---|---|
| Economic value of agricultural production | £/yr | 9.75E+08 | 1.34E+09 | 1.83E+09 | 1.90E+09 |
| Mass of agricultural production | g dry matter/yr | 1.56E+13 | 1.73E+13 | 1.74E+13 | 1.86E+13 |
| Energy content of agricultural production | J/yr | 1.85E+17 | 2.04E+17 | 2.04E+17 | 2.19E+17 |

**Table 1.9** Efficiency and performance indicators of the Scottish agricultural sector in selected years.

| | 1991 | 2001 | 2007 | 2010 |
|---|---|---|---|---|
| **Material resource depletion** | | | | |
| $MI_{abiot}$ (g/g d.m.) | 0.63 | 0.66 | 0.49 | 0.51 |
| $MI_{abiot}$ (g/€) | 6.62E+03 | 5.28E+03 | 3.16E+03 | 4.27E+03 |
| $MI_{abiot}$ (g/£) | 1.01E+04 | 8.49E+03 | 4.63E+03 | 4.98E+03 |
| $MI_{abiot}$ (g/J) | 5.31E-05 | 5.56E-05 | 4.15E-05 | 4.32E-05 |
| $MI_{abiot}$ (g/ha) | 5.55E+06 | 6.08E+06 | 4.62E+06 | 4.85E+06 |
| $Mi_{water}$ (g/g d.m.) | 2.49 | 2.53 | 1.80 | 1.88 |
| $MI_{water}$ (g/€) | 2.63E+04 | 2.03E+04 | 1.16E+04 | 1.57E+04 |
| $MI_{water}$ (g/£) | 4.00E+04 | 3.27E+04 | 1.70E+04 | 1.84E+04 |
| $MI_{water}$ (g/J) | 2.11E-04 | 2.14E-04 | 1.53E-04 | 1.59E-04 |
| $MI_{water}$ (g/ha) | 2.21E+07 | 2.34E+07 | 1.70E+07 | 1.79E+07 |
| Total abiotic material requirement | 9.81E+12 | 1.14E+13 | 8.48E+12 | 9.46E+12 |
| Total water Footprint | 3.90E+13 | 4.37E+13 | 3.12E+13 | 3.49E+13 |
| Global to Local Abiotic | 2.48 | 2.67 | 2.07 | 2.17 |
| Global to Local Water | 7.53 | 8.36 | 5.96 | 6.67 |
| **Energy resource depletion** | | | | |
| GER per unit of mass (J/g d.m.) | 1.42E+03 | 1.48E+03 | 1.23E+03 | 1.29E+03 |
| GER per unit currency (J/€) | 1.50E+07 | 1.19E+07 | 7.97E+06 | 1.08E+07 |
| GER per unit currency (J/£) | 2.27E+07 | 1.92E+07 | 1.17E+07 | 1.27E+07 |
| GER per unit of energy (J/J) | 0.12 | 0.13 | 0.10 | 0.11 |
| GER per ha (J/ha) | 1.25E+10 | 1.37E+10 | 1.17E+10 | 1.23E+10 |
| Oil eq. (g/g d.m.) | 0.03 | 0.04 | 0.03 | 0.03 |
| Oil eq. (g/€) | 357.65 | 284.74 | 190.44 | 259.18 |
| Oil eq. (g/£) | 543.34 | 458.05 | 279.37 | 302.46 |
| Oil eq. (g/J) | 2.87E-06 | 2.87E-06 | 3.00E-06 | 2.50E-06 |
| Oil eq (g/ha) | 3.00E+05 | 3.00E+05 | 3.28E+05 | 2.78E+05 |
| EROI (Energy of products/Total embodied energy applied) | 8.33 | 7.96 | 9.55 | 9.11 |
| Global to Local energy | 5.03 | 5.13 | 3.34 | 3.50 |
| **Emergy, demand for environmental support** | | | | |
| Specific emergy (with L&S) (seJ/g d.m.) | 6.53E+08 | 6.60E+08 | 6.32E+08 | 6.03E+08 |
| Emergy intensity (with L&S) (seJ/€) | 6.89E+12 | 5.30E+12 | 4.09E+12 | 5.05E+12 |
| Emergy intensity (with L&S) (seJ/£) | 1.05E+13 | 8.53E+12 | 6.00E+12 | 5.89E+12 |
| Transformity (with L&S) (seJ/J) | 5.53E+04 | 5.59E+04 | 5.37E+04 | 5.11E+04 |
| Empower density (with L&S) (seJ/ha) | 5.78E+15 | 6.11E+15 | 5.98E+15 | 5.74E+15 |
| Emergy Yield Ratio (with L&S) = U/(F+L+S) | 1.26 | 1.23 | 1.26 | 1.24 |
| Environmental Loading Ratio (with L&S) = (N+F+L+S)/(R) | 5.83 | 6.75 | 5.72 | 6.59 |
| Environmental Sustainability Index (with L&S) = EYR/ELR | 0.22 | 0.18 | 0.22 | 0.19 |
| **Climate change** | | | | |
| Global warming (Carbon footprint; $CO_2$-eq., g/g d.m.) | 0.13 | 0.13 | 0.11 | 0.11 |
| Global warming (Carbon footprint; $CO_2$-eq., g/€) | 1.33E+03 | 1.04E+03 | 7.15E+02 | 9.63E+02 |
| Global warming (Carbon footprint; $CO_2$-eq., g/£) | 2.02E+03 | 1.68E+03 | 1.05E+03 | 1.12E+03 |
| Acidification ($SO_2$-eq., g/g d.m.) | 8.28E-04 | 5.38E-03 | 6.53E-04 | 6.95E-04 |
| Acidification ($SO_2$-eq., g/€) | 8.74 | 6.98 | 4.22 | 5.82 |
| Acidification ($SO_2$-eq., g/£) | 13.27 | 11.22 | 6.19 | 6.80 |
| Eutrophication (PO4-eq., g/g d.m) | 4.21E-05 | 4.38E-05 | 3.74E-05 | 3.91E-05 |
| Eutrophication (PO4-eq., g/€) | 0.44 | 0.35 | 0.24 | 0.33 |
| Eutrophication (PO4-eq., g/£) | 0.67 | 0.57 | 0.35 | 0.38 |

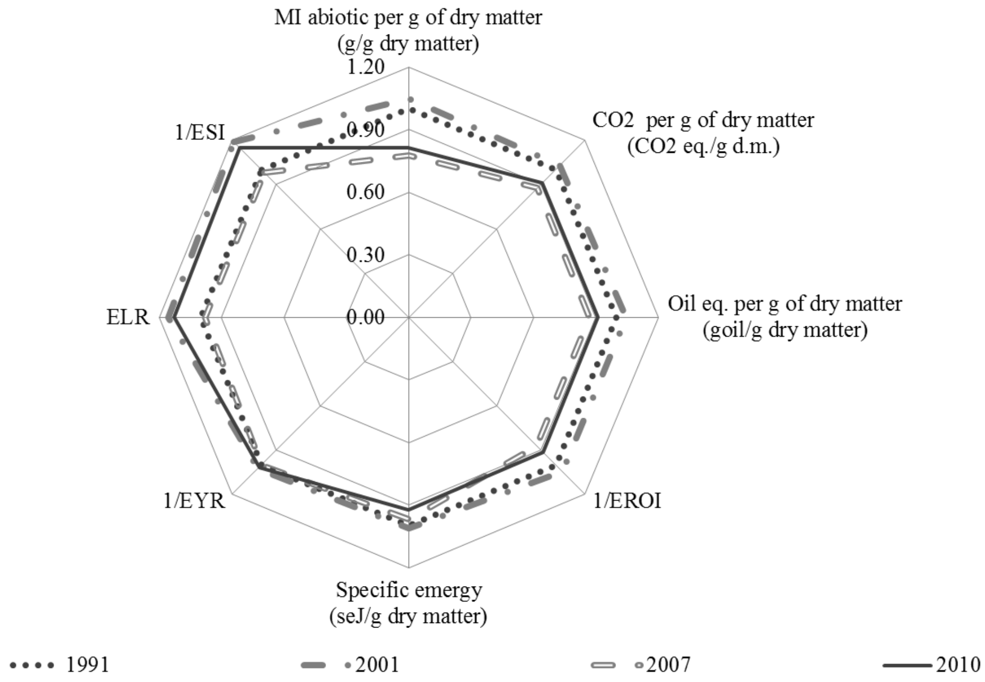


**Figure 1.10** The radar diagram shows the performance indicators of Scottish agriculture over time. Values normalized divided by the value of the first year of investigation from Table 1.9.

*Time trends of national agro-systems*

Trends of resource use, cropped land, labor invested, and yields harvested allow the calculation of performance and sustainability indicators for the two systems (Tables 1.7 and 1.9). Focusing on material and energy costs, it can be seen that 1 g d.m. of agricultural product required in Italy 2010 about 1 g of abiotic material (66% more than in 1985) and 3.3 kJ of energy (50% more than in 1985). Unit water demand dropped from 29.5 g water per g of product, more than 50% less compared to 1985. Instead, the Scottish agricultural system, in spite of its less favorable climate conditions, only required 0.51 g abiotic matter per g of product (20% less than in 1991) and 1.29 kJ of energy (9% less than in the reference year). Water demand dropped by 25% (from 2.49 g water per gram product in 1991 to 1.88 g water/g product in 2010). The much lower water use in Scotland is certainly due to the different climate conditions and mix of agricultural crops (e.g. wheat in Italy demanding more water than barley in Scotland); instead, the increase of abiotic material and energy demand in Italy is linked to the still intensive agricultural system (especially in Northern Italy), based on increasing mechanization and fuel use and doubling of electricity use, coupled to decreased agricultural yields (in mass and energy content terms) (Table 1.6). The opposite is true in Scotland, where electricity use decreases by about one third, coupled to increased yield. The energy investment compared to the energy content of the yield provides an additional information about the ability of the systems to capture and store the solar energy through photosynthesis: the EROI of Italian agriculture is constantly around the value of 7:1 (7 joule yielded versus 1 J fossil energy invested), while EROI is in the range 7-10:1 for Scotland (with an increasing trend), showing a much higher ability to capture the solar energy and making it available.

Of course, data trends oscillate in both countries and the final energy and material costs are the cumulative result of changes occurring in all input and product flows.

It is important to point out that the total current price economic value of agricultural production in Italy was 2.37E+10 € (28% higher than in 1985), compared to an economic expenditure of 2.36E+10 € in 2010, for labor and services: the activity was hardly capable to pay its own expenses, in the average. Instead, the Scottish agriculture still shows an economic value of agricultural production equal to 2.22E+09 € (in 2010, 50% higher than in 1991), compared to 1.65E+09 € in the same year, still providing a sufficient net income. The reasons for such trends must be investigated in individual input items of Tables 1.6 and 1.8, with special focus on the oscillations of each flow and their consequences on the final results.

Contributions to global warming, rain acidification and water body eutrophication are also shown in Tables 1.7 (Italy) and 1.9 (Scotland), globally showing a better performance of Scottish agriculture (smaller unit values and decreasing trends in all categories) compared to Italian agriculture (increasing trends and higher absolute unit values).

The emergy synthesis methods provide another interesting set of indicators. While mass and energy indicators shed light on the efficiency of the system in using available resources, emergy indices and ratios allow to investigate the quality of these resources. In other words, a system may be efficient in using fossil energies, but still be unsustainable due to their nonrenewability. Focusing on resource generation time and patterns, emergy assigns a quality label to each resource flow and calculates indicators of efficiency (transformities: solar equivalent energy/unit of product), local self-reliance (EYR= total emergy use/imported emergy), carrying capacity (ELR= nonrenewable and imported emergy/local renewable emergy), economic and environmental sustainability (ESI= EYR/ELR), renewability (%REN= renewable emergy use/total emergy use). Looking at the emergy indicators in Tables 1.7 and 1.9, it is possible to extract a clear picture of the performance of the two systems at the scale of biosphere, i.e. at the scale of the larger system that generates and provides resources over time. Very important is to point out that emergy accounting also includes the generation of minerals in the crust and other life-supporting processes, that are not included in material and energy accounting methods.

The demand for such environmental support doubled in Italian agriculture during the investigated time period: very interesting is to observe that while the emergy per unit mass (seJ/g d.m.) doubles, the emergy demand per unit economic value (seJ/€) only increases by 20% (inflation affects results to some extent) and the emergy demand per unit of energy delivered increased by 2.5 times, likely affected by a lowered energy content of the delivered product. The Sustainability Index (ESI) decreased from 0.14 in 1985 to 0.08 in 2010.

The Scottish agriculture shows a much better performance also in emergy terms: its emergy demand per unit of product (either g d.m., J and €) decreased, while its overall sustainability is more than twice the one for Italy and shows a slow decreasing trend.

*Large scale versus local scale burdens*

Tables 1.7 and 1.9 also show another set of interesting indicators, the so-called global to local ratios. They are defined as the ratio of cumulative material, energy, emission burden (indirect + direct investments) to the locally invested amounts, thus measuring how the local specificity of a process is capable to amplify the resource demand at larger scales. Considering, for example, the energy global-to-local ratio, its value close to 3 for Italy and close to 3.5 for Scotland means that each joule of energy used locally (directly in the farm) is supported by more or less 3 joules invested directly or indirectly in the process (also due to the energy invested for material goods like tractors and pesticides). A change in the amount or in the mix of direct energy and resources used locally affects the global scale, since it depends on the resource metabolism of the production chain (and process efficiency) that is followed to deliver the input resources and since there is energy embodied in goods, materials and infrastructures. For example, using steel locally involves the whole chain that provides such a steel, from mining of iron ore to the refining of the product in a life cycle perspective. Therefore, if more or less steel is used, or if steel is replaced by aluminum, or if recycling patterns are implemented, this may translate into a bigger or smaller burden placed on the larger scale. Global-to-local use ratios can be calculated for almost all impact categories (matter demand, water demand, impact of emissions): Tables 1.7 and 1.9 show an abiotic material global-to-local ratio of about 1.5 for Italian agriculture in 2010 and about 2.0 for Scotland (both decreasing trends). Similar ratios can also be calculated for water use and emissions, in order to highlight the burden generated outside of the local system and increase awareness for responsible and planned use of resources. Providing a clear assessment of such aspects is important for policy. The global-to-local ratios may change due to a multiplicity of factors (efficiency of the productive chain, mix of supply, etc.) and it is possible to affect these factors through improvement strategies.
The global-to-local ratio cannot be calculated for emergy that is by definition focused on the global scale only.

*Use of biophysical indicators for planning and policy making*

Once time series of inventories are made available (Tables 1.6 and 1.8) and a suitable set of performance and sustainability indicators has been calculated (Tables 1.7 and 1.9), it is possible to generate an overall comparison of the systems behavior over time (Figure 1.11) similar to the radar diagrams used for assessment of time trends (Figures 1.9 and 1.10). The Figure helps understand in a global way what are the parameters that affect to a larger extent the performance of each investigated system, so that it is easier to a manage, a stakeholder or a policy maker to go back to the analytical Tables

of calculated indicators, identify the most crucial and then refer to the inventory and the supply chain for suitable improvement actions and regulations.
Figure 1.11 suggests that the agriculture of Italy 2010 is globally more environmental impacting than the Scottish agriculture in the same year. The figure also includes material and energy flows per ha, higher for Italy than for Scotland. When indicators are calculated on "per gram" or per € basis, costs and impacts are hidden, because of the Italian higher productivity per hectare and because of the conversion ratio U.K £/€. Figures similar to Figures 1.9, 1.10 and 1.11 may be a useful starting point for a debate about a system's performance (not only an agricultural one), for comparison among systems, for scenario-making and for detailed discussion about the reasons and the drivers of calculated performances, in order to involve all potential actors in concerned policies and responsible use of resources.

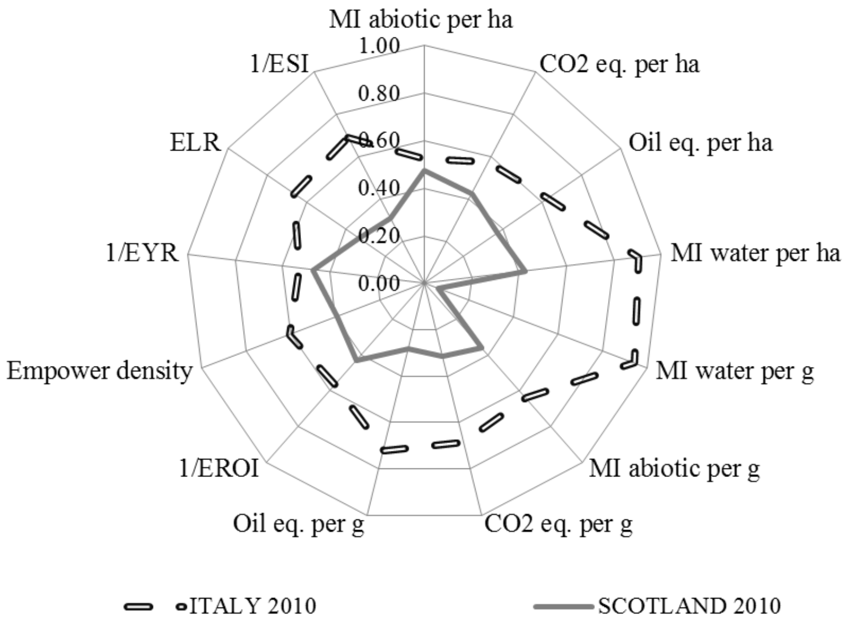


**Fig. 1.11** Radar diagram showing the comparison of the performance indicators of agriculture in Italy and Scotland. Values normalized with reference to the total impact generated (the total impact is calculated by adding the values of the two systems, then, in order to calculate its fraction or percentage, the value of the indicator is divided by the sum of the two) from Tables 1.7 and 1.9.

The two investigated case studies (Italian and Scottish agricultures) underlined a very different dynamics. The Italian agricultural system seems increasingly becoming less sustainable, because of its heavy dependence on fossil fuels. The Scottish system shows instead a better global performance. A problem suggested by the assessment is that the best performing system is not also the one characterized by the highest productivity. Such an aspect must be taken into account by policy makers, in that it affects the ability of the system to supply food, energy and materials to meet the growing needs of local populations.
It clearly appears that both investigated systems generate not only local but also and mainly global impacts in the surrounding regions where primary input are processed

as well as all over the supply chain. This means that an improvement of the local performance (efficiency, change of resource mix, change of crop mix, etc.) may lead to a positive feedback effect on the regional and global scales. The integrated approach presented and applied in this study is suitably designed in such a way to allow comparative assessment and "scenario making" experiments, based on selectively assuming technical changes or better use of the most crucial production factors in order to ascertain how these changes affect the final performance indicators.

## *C. Comparison with Polish agriculture.*

## *Environmental Assessment and comparison of Italian and Polish milk production*

### Introduction

The European agricultural policies are promoting a multifunctional role for the agricultural sector to increase its socio-economic and environmental sustainability (European Commission, 2012a). The agricultural phase in the life cycle of agro-food products and in particular of milk production critically contributes to the global warming, acidification and eutrophication potentials (Castanheira et al, 2010; Roy et al., 2009; Hospido et al., 2003).
Many Italian dairy farms, attracted by economic incentives, have been involved in the last years in innovation processes installing biogas or photovoltaic plants (Ragazzoni, 2013). The anaerobic digestion is one of the best options for the valorization of livestock effluents that are available as co-products in dairy farms (Angelidaki and Ellegaard, 2003; Edelmann et al., 2005; Maranon et al., 2011; Bacenetti et al., 2013; Pantaleo et al., 2013). However, the economic incentives, after their introduction, have been source of distortions favoring in particular the installation of large biogas plants (999 kWp) that in most cases end up to be fed by energy crops (e.g. cereals silage) instead of animal effluents (Carrosio, 2013; Ragazzoni, 2013). The Italian Government therefore revised the incentives (M.D. 6 July 2012) to favoring the use of agricultural and livestock residues as feedstock instead of energy crops (Bacenetti et al., 2012; Ragazzoni, 2013). The opportunity of recycling farm substrates is an essential prerequisite for the transition to circular economy in agriculture (European Commission, 2012b).
In this study, we analyzed the agricultural activities of a dairy farm located in northern Italy, producing milk. In 2011, the owners of the dairy farm, with the aim to increase the economic sustainability of their enterprise, installed a biogas plant (330 kWp) only fed by livestock farm effluents, and two solar PV plants mounted on the roof of the livestock holdings. While the electricity of PV plant is totally self-consumed to satisfy the electricity needs of the dairy farm, only a small part of the electricity from biogas plant is self-consumed while the surplus is sold to the energy market. In detail, the installation of the biogas plant zeroed the electricity dependence from the national grid, increased the income of the dairy farm, allowed the supply of renewable electricity to about 200 households and improved the social acceptability of this farm by reducing odor problems (Fabbri et al, 2011).
Many authors have already investigated the environmental impacts of dairy farm systems producing milk using different methods ranging from Life Cycle Assessment (Vitali et al., 2013; Fantin et al., 2012; Barti et al., 2011; Castanheira et al., 2010;

Kristensen, 2011; Penati et al., 2010; Basset-Mens et al., 2009; Thomassen et al., 2008; De Boer, 2003; Hospido et al., 2003), Energy Analysis (Gomiero et al., 2008; Refsgaard et al, 1998) and Emergy Synthesis (Jaklič, 2013; Rotolo et al., 2011; Brandt-Williams and Lagerberg, 2005).
With our study, we evaluated the environmental and energy impacts (according to different perspectives) before and after the substitution of fossil-based electricity from the national mix by means of the renewable one produced by the farm. We also compared the performances of this Italian dairy farm with the ones of another farm located in Poland. At World level, Italy and Poland are among the top twenty milk producers (FAOSTAT, 2012).

*The investigated systems*

Two dairy farms, one in Italy and one in Poland, were investigated (Figure 1.19). The Italian farm has been investigated before (Scenario 1) and after (Scenario 2) the installation of solar PV and biogas plants. The Italian farm is located in Emilia Romagna Region, the area of production of the famous Parmigiano Reggiano cheese that includes the provinces of Parma, Reggio Emilia, Modena and parts of the province of Mantova and Bologna between the Po and Reno rivers. In this area about 4000 dairy farms produce milk for the production of Parmigiano Reggiano. As Parmigiano Reggiano is a product marked with the label PDO (Protected Designation of Origin) its productive characteristics are strictly related with the area of origin and are guaranteed by rules designed by the European Union to protect both consumers and producers (Parmigiano Reggiano Consortium, 2011a). The regulation of production defined by the Consortium establishes that the dairy cows should mainly be fed with local grass coming from the Region of Origin and natural animal feed. In the cows diet any type of silage including slop feed, the use of forages heated by fermentation, treated with additives, forage contaminated by parasites, decayed, soiled or contaminated by toxic, radioactive or noxious substances, etc., are forbidden (Parmigiano Reggiano Consortium, 2011b).
The climate is temperate continental with strong temperature differences between summer and winter. Winter temperature may go below 0 °C while it may be over 30 °C with a high level of humidity in summer. Rainfall ranges between the 600-800 mm per year.


**Figure 1.19.** Location of the two investigated farms. Arable farmland in yellow, forest in dark green, pasture in light green, and tundra or bogs in dark yellow. (Source: http://en.wikipedia.org/wiki/File:Europe_land_use_map.png)

The herd of the Italian farm consists of 1850 (1415 Livestock Units[3]) Friesian cows; with 850 dairy cows in lactation yielding on average 7,760 kg of milk per year. The total annual production of milk in 2011 amounted to 6,600 tons. The arable land of dairy farm devoted to the cultivation of the crops (alfalfa, ryegrass and maize) used as fodder for the cattle reaches 380 hectares. The farm employs 14 agricultural workers. The Polish farm is located in the south-western part of the country, between the provinces of Poznan and Wroclaw, characterized by climate conditions suitable to agricultural production including longer vegetation season in comparison with other parts of Poland. The total rainfall amounts to 500-600 mm per year. The winter temperature goes below 0 °C, while the summer temperature can be higher than 30 °C. The farm couples milk production with pedigree breeding and as a result annual milk yield per cow in the farm is considerably higher than average annual milk yield per cow in Poland. Moreover, some innovations are implemented in cows' feeding, as carrot added to corn silage. The farm is equipped with machines to harvest and produce silage supported by fermentation additives. The barns for dairy cattle are equipped with cooling fans, walls with curtains and lying stalls with straw in order to create appropriate welfare conditions for the cows. In the farm, 1810 cows are reared with 980 dairy cows in lactation and amounting to 1478 Livestock Units. In 2011 the average milk yield per cow has been of 10,651 kg while the annual production of milk 10,438 tons.

The arable land of the dairy farm for cropping cultivation (rape, grass, green maize fodder, corn, barley wheat, sugar beets) is 950 hectares, with 50 agricultural workers.

[3] The Livestock unit is a standard reference unit that allows the aggregation of the various categories of livestock (various species, sex and age) in order to enable them to be compared. Statistical Office of Poland: http://www.stat.gov.pl/gus/definicje_ENG_HTML.htm?id=ANG-5234.htm . The coefficients are: 1 for dairy cows, 0.40 for cattle of age younger than 1 year (calves) and 0.70 for female bovines of age between 1 and 2 years.

*Data collection*

Data about inputs used in the two dairy farms have been collected through direct interviews to the owners. Inputs are referred to the years 2010 (Scenario 1) and 2011 (Scenario 2) for the Italian farm and to the year 2011 for the Polish farm. The two farms use the manure or the biogas digestate (in the case of the Italian farm Scenario 2) for agronomic purposes, reducing the amount of purchased chemical fertilizers. The irrigation water demand in the Italian dairy farm has been estimated from Ribaudo (2009). For the livestock activities we calculated 175 liters of water per cow per day from Rossi et al. (2008) who monitored the consumption of water use for dairy cows (with different type of stalling and average production of milk for single lactation) in a project financed by the Emilia Romagna Region. The consumption of water of the Polish farm is based on farm data. The Polish farm does not use water for irrigation of the arable land.

The daily ration of Italian dairy cows consists of alfalfa hay (30%), Italian ryegrass hay (*Lolium multiforum Lam*.) (23%), maize meal (17%), maize flakes (5%), soil meal (5%), complementary fodder (17%), wheat straw (3%). The daily feed ration amounts to 28.7 kg of fresh matter (20.06 kg of dry matter). Instead, the Polish livestock daily ration amounts to a much higher 60.5 kg fresh matter, broken down into 53% of grass (perennial grasses like fescue, timothy and rye grass), green maize fodder (21%), sugar beet (11%), nutritive fodder (3%), wheat (3%), soybean (2%), beet pulp (2%), rape (2%), spent grain (1%), barley (1%), and corn (1%).

Data of the renewable (sunlight, wind, rainfall, geothermal heat) and local non-renewable (topsoil) input flows are taken from the official Italian (European Commission, 2012c; ISPRA, 2011; ISTAT, 2010; CNR, 1986) and Polish environmental statistics (http://www.stat.gov.pl/gus/index_ENG_HTML.htm).

With regard to the output, we collected data related to the following items:

- *For the Italian Farm:* crops (alfalfa, Italian ryegrass and maize), crops residues (maize stalks and cobs), milk and cow effluents (solid and liquids). In the year 2011 (scenario 2) the farm produced electricity from solar photovoltaic and biogas.
- *For the Polish Farm*: crops (grass, green maize fodder, barley, maize, sugar beet, wheat and rape), crops residues (wheat straw, maize stalks and cobs), milk and cows effluents (solid and liquids).

In order to obtain the annual output (crops, crops residues, milk, effluents) also in terms of dry matter and energy content, the output data in physical quantity have been converted into their dry matter mass and energy values by means of water content and energy equivalence factors from INRAN database (Italian National Institute for Research in Food and Nutrition)[4].

The main process emission flows were:

[4] INRAN, www.inran.it

- direct and indirect emissions associated to electricity consumption (considering the Italian and Polish electric mix) and fuel consumption, calculated by means of the CORINAIR (2007) emission model;
- direct and indirect $N_2O$ emissions from chemical fertilizers application, calculated according to the Report of National Emissions in Agriculture 2011 of the National Advanced Institute for the Environmental Protection and Research (ISPRA, 2011; IPCC guidelines, 1997, 2000).
- direct $CH_4$ emissions from enteric fermentation, calculated according to UNFCCC[5] (2013);
- direct $NH_3$ emissions due to the application of nitrogen fertilizers, calculated on the basis of EMEP/CORINAIR (2007) and EMEP/EEA (2009[6]).
- direct emissions of $CH_4$, $N_2O$, $NH_3$ due to manure and digestate storage and soil application, quantified using the coefficients of Amon et al. (2002, 2006).

**Methods**

The direct and indirect impacts of the dairy farms operations starting from the production of crops for animal feed until the production of raw milk at dairy farm gate were investigated.
In order to explore different aspects of the investigated systems, the following impact assessment methods were applied: Material Flow Accounting (Schmidt-Bleck, 1993; Hinterberger and Stiller, 1998; Bargigli et al, 2004; Wuppertal Institute, 2013), fossil Cumulative Energy Demand (Ulgiati, 2009; Herendeen, 1998; Slesser, 1978), Life Cycle Assessment (CML 2001, for impacts of emissions), Emergy Synthesis (Odum, 1998, 1996; Brown and Ulgiati 2004a,b). The latter integrates the analysis of the impacts related to the direct and indirect use of materials and commercial energy flows with the broader context of resource generation by natural processes, demand for environmental support and ecosystem services. Based on the amount of direct and indirect environmental work converging to the generation of one unit of resource, the emergy method assigns quality factors (transformity or UEV-Unit Emergy Value) to resource flows used in the process, measured in terms of solar equivalent joules (sej/J,

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[5] The emission factors used for the calculation of direct air emission of $CH_4$ from enteric fermentation and manure management (kg $CH_4$/head/year) and the emissions factors (kg $N_2O$-N/kg N) for direct and indirect emissions of $N_2O$ are country specific for Poland (2011 year) and Italy (2010 and 2011 years). See the National Inventory Submissions of United Nations, Framework Convention on Climate Change published for all the parties in the Annex I of the Convention: The National Inventory Report contains detailed descriptive and numerical information and the Common Reporting Format contains summary, sectorial and trend tables for all greenhouse gas (GHG) emissions and removals, and sectorial background data tables for reporting implied emission factors and activity data, available: http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/5888.php

[6] http://www.eea.europa.eu/publications/emep-eea-guidebook-2013/#

sej/g, sej/$, etc). For detailed description of each method, the reader may like to refer to the indicated literature.

Figure 1.20 shows a systems diagram representing the Italian dairy farm system integrated by the PV and biogas plants. The diagram, drawn according to the standardized energy systems language (Odum, 1996), serves as a basis to develop the quantitative inventory of input and output flows. It shows in a pictorial way the main driving forces, producers, consumers, storages, and interactions among the system's components. Driving forces and system's components were drawn from left to right on the basis of increasing environmental quality (*i.e.*, increasing transformity) highlighting in such a way the resource use hierarchy characterizing the two dairy farm systems (Franzese et al., 2013).

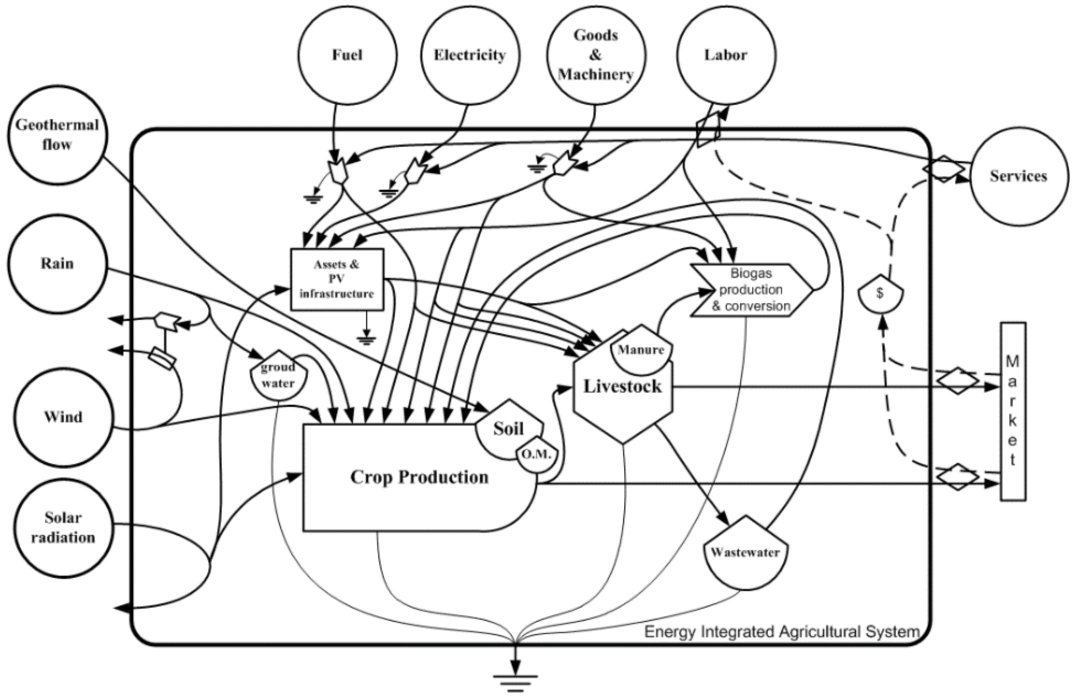


**Figure 1.20**. System diagram of the Italian farm (Scenario 2).

After the compilation of the inventory, energy and emergy intensities and LCA characterization factors collected from literature were applied (Bargigli & Ulgiati, 2003; Biondi et al., 1988; Brown & Ulgiati, 2004a,b; Buenfil, 2000; Cavalett and Ortega, 2009; Cialani et al., 2005; Fahd, 2011; Franzese et al., 2013; Hauschild & Wenzel, 1988; IPCC, 2007; Odum, 2000; Ulgiati & Russi, 1999; Wuppertal Institute, 2009; 2013) according to each method's principles, algebra and interpretazion framework.

Allocation procedures

We applied the allocation method per economic value as the dairy farms produce milk and meat (and electricity in the case of the Italian farm) from the same production process as well as crops production for animal feed and for the market (only in the case of Polish farm) and crops residues from the same unique process. With the allocation method we determined the environmental impacts among the co-products. The distribution of the impacts in the Italian farm in the scenario 2 resulted: 83.43% to milk, 8.77% to meat and 7.80% to electricity. For crops production the environmental impacts allocated resulted: 96.59% to crops and 3.41% to crops residues (maize stalks and cobs). As they are used as animal bedding we attributed the same price of wheat straw that is commonly used as animal bedding material and has a market value. For the Polish farm the environmental impacts have been allocated in the livestock subsystem as follows: 88.43% to milk, 11.57% to meat while in the crops subsystem: 83.19% to crops for animal feed, 13.21% to crops sold to the market and 3.60% to crops residues.

*Results*

Tables 1.18 and 1.19 summarize the annual input and output (final products) of the two dairy farms in crop and livestock subsystems. Where specified, input and output are referred only to the Scenario 1 or 2 of the Italian farm.

**Table 1.18.** Inventory of the crop subsystems.

| | Unit | Italian farm | Polish farm |
|---|---|---|---|
| Total arable land | ha | 3.80E+02 | 9.50E+02 |
| **Input** | | | |
| Sun | J/yr | 1.56E+16 | 2.74E+16 |
| Wind | J/yr | 3.91E+13 | 1.46E+14 |
| Rainfall | J/yr | 8.78E+12 | 9.90E+12 |
| Deep heat | J/yr | 6.39E+12 | 1.95E+13 |
| Lubricants | kg/yr | 1.95E+02 | 6.86E+01 |
| Gasoline | kg/yr | - | 4.29E+02 |
| Agricultural Diesel | kg/yr | 1.01E+05 | 9.30E+04 |
| Water for irrigation | $m^3$/yr | 5.28E+04 | - |
| Seeds | kg/yr | 1.06E+03 | 4.04E+04 |
| Manure (only for Scenario 1) | kg/yr | 3.53E+07 | 2.46E+07 |
| Digestate (only for Scenario 2) | kg/yr | 3.39E+07 | - |
| Nitrogen (N) | kg/yr | 1.32E+03 | 1.64E+04 |
| Phosphate ($P_2O_5$) | kg/yr | 2.20E+03 | 5.80E+03 |
| Potassium ($K_2O$) | kg/yr | - | 7.20E+03 |
| Lime 60% CaO | kg/yr | - | 4.00E+02 |
| Fungicides | kg/yr | - | 3.20E+02 |
| Insecticides and Acaricides | kg/yr | - | 4.30E+02 |
| Herbicides | kg/yr | 1.54E+02 | 4.60E+02 |
| Agricultural machinery | kg/yr | 2.28E+03 | 1.13E+03 |
| Direct labor | $/yr | 5.02E+04 | 6.60E+04 |
| Indirect labor (services) | $/yr | 1.51E+05 | 2.66E+05 |
| **Output** | | | |
| Crops for animal feed | kg/yr | 6.53E+06 | 2.54E+07 |
| Crops sold to the market | kg/yr | | 2.89E+06 |
| Crops residues | kg/yr | 4.41E+05 | 1.15E+06 |

**Table 1.19.** Inventory of the livestock subsystems.

| | Unit | Italian | Polish farm |
|---|---|---|---|
| Cows in lactations | n./yr | 850 | 980 |
| Other cows in the herds | n./yr | 1000 | 1810 |
| | | | |
| **Input** | | | |
| Sun | J/yr | 9.58E+14 | 4.32E+15 |
| Wind | J/yr | 2.42E+12 | 2.31E+13 |
| Rainfall | J/yr | 5.40E+11 | 1.56E+12 |
| Deep heat | J/yr | 3.94E+11 | 3.07E+12 |
| Lubricants | kg/yr | 1.79E+02 | 9.70E+01 |
| Gasoline | kg/yr | - | 6.06E+02 |
| Agricultural Diesel | kg/yr | 1.30E+05 | 4.29E+04 |
| Electricity (Scenario 1) | kWh/yr | 3.91E+05 | 2.17E+05 |
| Electricity from solar PV (Scenario 2) | kWh/yr | 1.55E+05 | - |
| Electricity from Biogas (Scenario 2) | kWh/yr | 1.91E+05 | - |
| Water | $m^3$/yr | 1.18E+05 | 6.92E+04 |
| Agricultural machinery | kg/yr | 2.11E+03 | 1.59E+03 |
| Straw produced | kg/yr | 4.41E+05 | 1.15E+06 |
| Straw purchased | kg/yr | 1.25E+06 | 5.02E+05 |
| Animal feed produced | kg/yr | 6.10E+06 | 2.54E+07 |
| Animal feed purchased | kg/yr | 6.45E+06 | 2.67E+06 |
| Direct labor | $/yr | 3.01E+05 | 5.94E+05 |
| Indirect labor (services) (Scenario 1) | $/yr | 2.51E+06 | 8.10E+05 |
| Indirect labor (services) (Scenario 2) | $/yr | 2.42E+06 | - |
| | | | |
| **Output** | | | |
| Raw milk | kg/yr | 6.60E+06 | 1.04E+07 |
| Meat | kg/yr | 5.10E+05 | 2.32E+05 |
| Solid manure used in farm | kg/yr | 1.40E+07 | 9.84E+06 |
| Liquid manure used in farm | kg/yr | 2.13E+07 | 1.48E+07 |
| Electricity from Biogas Plant sold to the energy market (Scenario 2) | kWh/yr | 1.54E+06 | - |

Table 1.20 lists the main calculated indicators for the two crop production systems. Only the Scenario 2 is reported for the Italian farm, since no significant changes occurred in the two years investigated as far as the agricultural subsystem is concerned. In fact, the only difference is the replacement of manure fertilization with digestate fertilization, both of which from inside the farm (see Table 1.18). Calculated indicators per unit of product and per hectare of crop production show a worst performance of the Italian farm compared to the Polish one.

Table 1.21 shows the calculated indicators of milk production of the Italian farm for both Scenarios as well as for the Polish farm. The self-produced electricity by the Italian farm in the year 2011 (Scenario 2) globally improved the performance of the livestock subsystem. However, it clearly appears from Table 1.21 that also the livestock subsystem of the Polish farm had a better performance and a lower environmental impact compared to the same subsystem of the Italian farm.
Figures 1.21, 1.22 and 1.23 show the relative contribution of the different input supporting milk production for both Scenarios 1 and 2 of the Italian farm and for the Polish farm.

| Milk production | Italian Farm Scenario 1 (year 2010) | Italian Farm Scenario 2 (year 2011) | Italian Farm without agric. Phase | Polish Farm Scenario 1 (year 2011) |
|---|---|---|---|---|
| **Abiotic material and water use** | | | | |
| $MI_{abiot}$ (kg/kg) | 1.09 | 0.93 | 1.09 | 0.22 |
| $MI_{water}$ (kg/kg) | 24.37 | 19.59 | 24.10 | 6.82 |
| **Energy use** | | | | |
| Energy use per unit mass (MJ/kg) | 4.21 | 3.19 | 4.25 | 1.38 |
| Output/Input Energy Ratio | 0.64 | 0.84 | 0.63 | 1.95 |
| Global to local Energy ratio | 4.16 | 3.49 | 4.24 | 5.86 |
| **Emergy, demand for environmental support (with L&S)** | | | | |
| Specific emergy (seJ/kg) with L&S | 2.55E+12 | 2.46E+12 | 3.78E+12 | 9.60E+11 |
| EYR | 1.25 | 1.25 | 1.03 | 1.23 |
| ELR | 13.71 | 11.14 | 28.62 | 4.28 |
| %REN (with L&S) = 1/(1+ELR) | 0.07 | 0.08 | 0.03 | 0.19 |
| **LCA impact categories (CML 2001)** | | | | |
| Climate change GWP 100a (kg $CO_2$ eq./kg) | 1.16 | 0.73 | 1.14 | 0.51 |
| Acidification potential (kg $SO_2$ eq./kg) | 3.07E-03 | 2.61E-03 | 1.44E-03 | 1.09E-03 |
| Eutrophication Potential (kg $PO_4$ eq./kg) | 5.27E-04 | 4.68E-04 | 2.16E-04 | 1.82E-04 |

**Table 1.20.** Calculated indicators of the crop production subsystems.

**Table 1.21.** Calculated indicators of the livestock (milk) production subsystems.

| Crop production | Italian Farm | Polish Farm |
|---|---|---|
| **Abiotic material and water use** | | |
| $MI_{abiot}$ (g/g) | 0.03 | 0.02 |
| $MI_{abiot}$ (kg/ha) | 447.92 | 473.70 |
| $MI_{water}$ (g/g) | 7.98 | 0.05 |
| $MI_{water}$ (kg/ha) | 1.37E+05 | 1.32E+03 |
| Global to local ratio of abiotic material | 1.62 | 1.14 |
| Global to local water ratio | 1.02 | 0.00 |
| **Energy use** | | |
| Energy use per fresh matter (J/g) | 851.41 | 165.17 |
| Energy use per hectare (MJ/ha) | 1.46E+04 | 4.41E+03 |
| Ouptut/Input Energy Ratio | 15.06 | 72.14 |
| Global to local Energy ratio | 1.24 | 1.58 |
| **Emergy, demand for environmental support** | | |
| Specific emergy (seJ/g) with L&S | 2.15E+08 | 5.92E+07 |
| EYR with L&S | 1.26 | 1.28 |
| ELR with L&S | 4.00 | 3.80 |
| %REN (with L&S) = 1/(1+ELR) | 0.20 | 0.21 |
| **LCA Impact categories (CML 2001)** | | |
| Climate change GWP 100yr (kg $CO_2$ eq./kg) | 0.07 | 0.02 |
| Climate change GWP 100yr (kg $CO_2$ eq./ha) | 1.17E+03 | 5.43E+02 |
| Acidification Potential (kg $SO_2$ eq./kg) | 2.16E-03 | 2.42E-04 |
| Acidification Potential (kg SO2 eq./ha) | 37.12 | 6.47 |
| Eutrophication Potential (kg PO4 eq./kg) | 4.10E-04 | 4.79E-05 |
| Eutrophication Potential (kg PO4 eq./ha) | 7.05 | 1.28 |

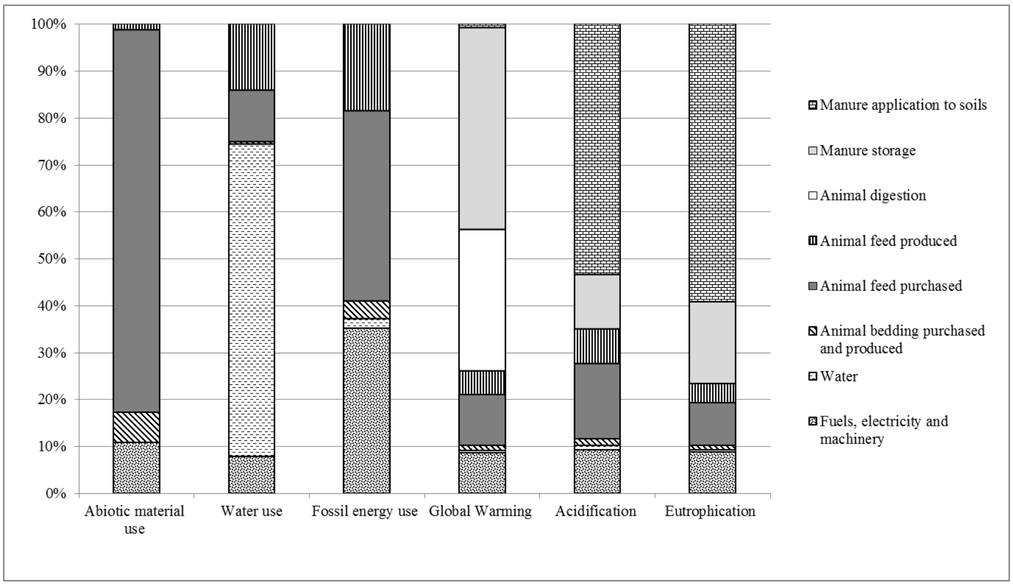


**Figure 1.21**. Relative contribution of each input to the impact categories of the milk production in the Italian farm (Scenario 1).

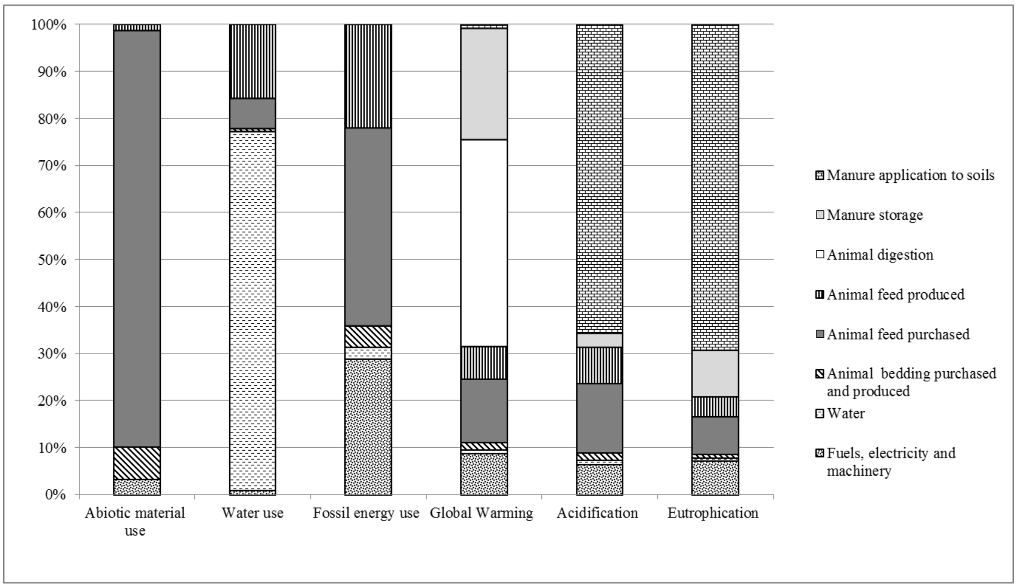


**Figure 1.22**. Relative contribution of each input to the impact categories of the milk production in the Italian farm (Scenario 2).

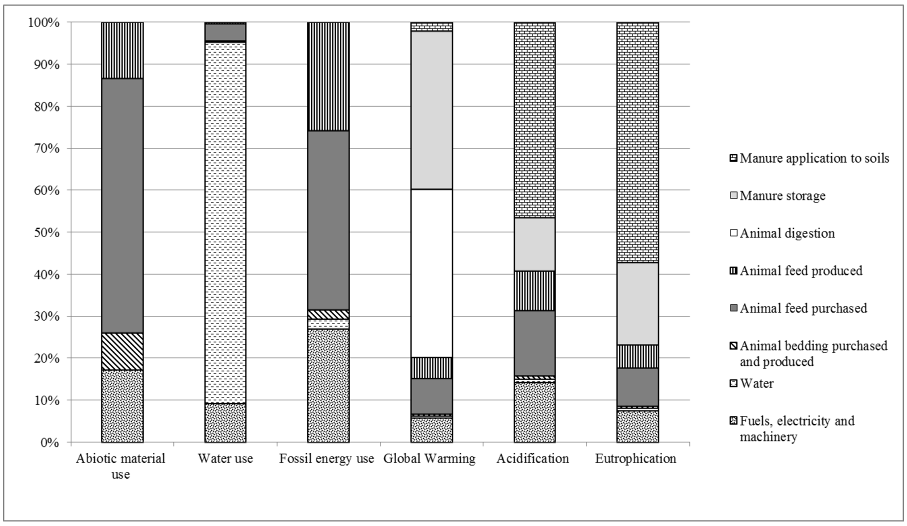


**Figure 1.23**. Relative contribution of each input to the impact categories of the milk production in the Polish farm.

*Direct and indirect abiotic material and water depletion*

The depletion of abiotic material related to the production of 1 kg of milk decreased from 1.09 $kg_{abiot}$ (scenario 1) to 0.93 $kg_{abiot}$ (scenario 2) in the Italian farm, while for the Polish farm the value amounted to 0.22 kg per kg of milk, about one forth. As shown in Figures 1.21, 1.22 and 1.23, the animal feed purchased, in the Italian farm, is the largest source of abiotic depletion, accounting respectively for 82% of the total impact in the scenario 1 and 89% in the scenario 2. Electricity in scenario 1 is the second highest contributor to abiotic material depletion, while in scenario 2 purchased animal bedding and agricultural diesel are the second and third most important items, respectively 7% and 2% of total impacts. In the Polish farm, more than one half of the total abiotic material depletion (61%) originates from purchased animal feed, followed by self-produced animal feed (13%) and electricity (15%).
The water resource depletion per kg of milk decreased by 20% in the Italian farm from scenario 1 to scenario 2 (Table 4). In this farm water depletion was three times higher (19.59 $kg_{water}$) than the Polish one (6.82 $kg_{water}$). Out of the total water amount, consumption for livestock (drinking, cleaning, feeding, cooling etc.) contributes to a large fraction of total withdrawal, namely about 66.5% (scenario 1) and 76.3% (scenario 2) in the Italian farm followed by electricity (7.2%) in scenario 1 and animal feed produced (15.7%) in scenario 2. In the Polish farm most of the impacts comes from water for livestock purposes (86.0%) and electricity (8.8%).

*Fossil Energy depletion*

The fossil energy demand of the Italian farm decreased by 24% from scenario 1 (4.21 $MJ/kg_{milk}$) to scenario 2 (3.19 $MJ/kg_{milk}$). Energy demand by the Polish farm was much lower than for the Italian farm accounting for only 1.38 $MJ/kg_{milk}$. In the scenario 1 of the Italian farm, most of the energy consumption was related to animal feed purchased

(42%) and produced (19%), diesel (23%), and electricity (11%). In the scenario 2 the relative contribution of diesel increased (up to 29% of the total) and so did animal feed purchased (42%) and produced (21%).
In the Polish farm most of the fossil energy for milk production was also related to the animal feed purchased (43%) and produced (26%), agricultural diesel (14%) and electricity (12%), although in much lower absolute amounts.

*Downstream environmental impacts*

In the Italian farm, the global warming potential (GWP) was 1.16 kg $CO_2$ eq. per kg of milk in scenario 1 and 0.73 kg $CO_2$ eq. per kg of milk in scenario 2, thus decreasing by 37%. In the Polish farm, the contribution to the GWP was 0.51 kg $CO_2$ eq. per kg of milk. In both farms most of the impacts are related to the local emissions of $CH_4$ and $N_2O$ from dairy from enteric fermentation (43.8% in the Italian farm scenario 2 and 40.0% in the Polish farm) and manure storage (respectively 23.6% in the Italian farm scenario 2 and 37.7% in the Polish farm).
The local emissions on dairy farm are pointed out as critical aspects also in other studies carried out in Italy (Vitali et al., 2013; Pignedoli et al., 2013) and elsewhere (Kristensen, 2011; Castanheira et al., 2010; De Boer, 2003; Hogaas, 2002; Cederberg and Mattson, 2000). In particular, Pignedoli *et al*., 2013, analyzing the carbon footprint (GWP 100 year frame) of six dairy farms also producing raw milk for Parmigiano Reggiano cheese calculated values from 0.86 kg $CO_2$ eq. to 0.98 kg $CO_2$ eq./kg of milk. In their study the emissions of $CH_4$ from animal digestion process accounted for the largest impacts (about 50-40% of the total emissions) with lower emissions from the production of feed (about 30% of the total) and manure storage (about 10% of the total).
The acidification potential, expressed as kg $SO_2$ eq. per kg of milk, decreased by 15% from 0.0031 kg $SO_2$ eq. (scenario 1) to 0.0026 kg $SO_2$ eq. (scenario 2). The contribution to the acidification potential of Polish farm was only 0.0011 kg $SO_2$ eq. per kg of milk. In both farms the impacts were mainly caused by manure and fertilizers application to soil, accounting for 53% (scenario 1) and 65.5% (scenario 2) of the total acidification in the Italian farm and 46.5% in the Polish farm.
Finally, the eutrophication potential in terms of kg of $PO_4$ eq. per kg of milk decreased by 11% in the Italian scenario 2 (4.68E-$0_4$ kg $PO_4$ eq./kg of milk). In the Polish farm the contribution was lower, namely 1.82E-04 kg $PO_4$ eq./kg of milk. As in the case of acidification potential the largest responsible were the application to soil of manure and fertilizers ($NH_3$ emissions), representing 69% of the total contribution in the Italian farm and 57% in the Polish farm.

*Emergy: demand for environmental support*

The specific emergy per kg of milk produced in the Italian farm resulted 2.55E+12 seJ/kg (scenario 1) and 2.46E+12 seJ/kg (scenario 2) decreasing by 3.6%. In the Polish farm the specific emergy resulted about three times less, 9.60E+11 seJ/kg. The ELR decreased by 18.8% in the scenario 2 (11.14) while the fraction of renewable emergy supporting the process slightly increased to (a still low) 8% and the EYR remained stable to 1.25. The ELR for the Polish farm is 4.28, while the fraction of renewables (%REN) is 19%.

In both scenarios of the Italian farm, as shown in Figure 1.24, a large emergy flow is provided in the form of non-renewable fraction of services, accounting for 39% of total emergy, followed by animal feed and purchased bedding (31% of the total emergy in the Scenario 2). Also in the Polish farm, the non-renewable fraction of services (21%) and purchased animal feed and bedding (21%) have the largest fractions.

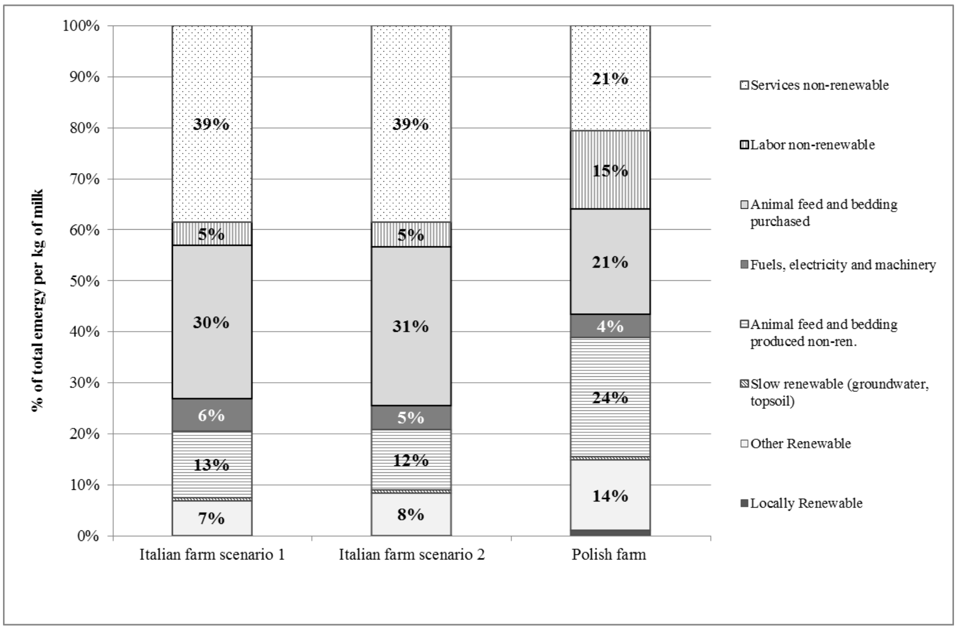


**Figure 1.24.** Breakdown of emergy input to total emergy supporting the milk productions.

## Discussion

*Comparing the Italian farms scenarios*

All the impact indicators calculated in this study for the Italian farm improved after the replacement of the grid electricity with electricity generated from farm mix (solar PV and biogas). In particular, the contribution to GWP decreased by 37% as a consequence of the reduction of $CO_2$ emissions from fossil-based electricity and of $CH_4$ emissions from the change of manure storage options (from untreated to digested manure) introduced after the installation of the biogas plant. Although $N_2O$ emissions increased due to the change of manure storage option (+22%), the combined reduction of $CO_2$ and $CH_4$ emissions has been much higher leading to decreasing total $CO_2$ eq. emissions.

The reduction of direct and indirect abiotic material use (-15%) and fossil energy demand (-24%) per kg of milk are also important, since the extraction, production and transport of fossil fuels for the production of grid electricity implies large quantities of materials to be extracted, as well as the consumption of energy and water in the supply

chain upward and elsewhere (Ulgiati et al., 2011). The global-to-local energy ratio also decreased from 4.16 to 3.49 in the transition confirming the decrease of the investment of fossil energy outside the dairy farm system per unit of energy consumed inside the dairy farm.
Compared to the national and regional milk production sectors, performances the fossil energy demand of the Italian farm (3.43 $MJ/kg_{milk}$) is lower. Ghisellini et al (2013, 2014) calculated average values of 5.59 MJ/kg and 4.98 MJ/kg of cow milk for the regional and national cow milk production respectively.
The Output/Input Energy ratio for the Italian farm milk production is 0.85 compared to 0.48 and 0.54 achieved in the regional and national cow milk. These results confirm that the efficiency of livestock sector in intensive agricultural systems (in developed countries) is low and never above 1:1 (Ghisellini et al., 2013, 2014).
The emergy indicators for a comprehensive analysis of the performances and sustainability in the transition from scenario 1 to scenario 2 also show interesting aspects, informing us about the use of all the type of natural resources (renewable and non-renewable) by the investigated systems. In its inventory (Tables 1.18 and 1.19) the emergy analysis includes the accounting of renewable and nonrenewable flows of rain, irrigation water, hours of direct and indirect labor, steel of machinery, fertilizers, etc. These types of inputs also have an energy value (that can be accounted e.g. according to the rules of embodied energy analysis) but their production was supported by the "environmental work" performed by the biosphere (sun, heat geothermal and gravitational potential). Inclusion of the environmental work allows a better knowledge of the performances of the dairy farms activities and an evaluation of their sustainability. Based on the work performed by Nature for the production of the goods and services, emergy analysis allows understanding the hierarchy of resources used and creates a starting point for improvements. The higher is the emergy of an input, the higher the environmental costs and support needed for its provision to the production chain, and therefore the supply-side quality of an item.
The total emergy supporting milk production decreased by 3.6 % in the transition between the two scenarios while the Environmental Loading Ratio decreased by 18.8%, down to 11.14. This indicator evidences the potential stress to the local renewable resources, exerted by the use of nonrenewable inputs imported from outside the local system. The regional and national livestock sectors present a better balance among the different types of emergy resources, resulting into lower ELRs: 8.32 (regional level) and 7.44 (national level). The results for EYRs of the Italian farms (1.14) are instead similar to the regional (1.14) and national scales (1.12) (Ghisellini et al, 2013, 2014).
The reliance on locally renewable resources is more or less the same in the two scenarios representing only the 8% of the total emergy resources used. These performances are closer with the ones of other studies analyzing dairy farm milk productions. Jaklic (2013) compared extensive and intensive milking systems in Slovenia calculating values of ELR ranging from 32.40 (renewable fraction: 3%) for highly intensive milking systems to 7.43 (renewable fraction: 12%) for extensive

milking systems, while Rotolo *et al*, 2010 calculated lower values for ELRs equal to 4.87 (renewable fraction: 17%) of an Argentinian farm case study.

*Comparing the performances of the Italian and Polish dairy farms*

The Polish dairy farm seems to perform better compared to the Italian one in all the investigated impact categories evidencing a better efficiency in the use of abiotic material, water resources, fossil energy and environmental support. Its Emergy Yield Ratio is almost the same as for the Italian farm (1.23), while its Environmental Loading Ratio is 4.28 (lower than for the Italian farm, but still indicating a high load) and the fraction of renewable emergy resources consumed is a low 19% suggesting non-renewable and imported emergy resources still being the dominating driver. The comparison shows common critical factors for the two farms mainly related to the production of feed purchased from outside, to the use of diesel in agricultural operations and to the application of fertilizers (both, organic and chemical).
The application of manure to the agricultural soils reduces the purchase of chemical fertilizers while at the same time exerting an environmental pressure due to $CH_4$ emissions, ammonia emissions and dinitrogen monoxide emissions by these effluents during their degradation in the soil. The anaerobic digestion of livestock effluents reduces the potential contribution to GWP as a result of the prevention of these emissions. In fact, the amount of released methane in the stage of soil application of effluents is inversely related to the time of their permanence in the anaerobic digestion plant: the longer the time in the anaerobic digestion plant the smaller the amount of methane emissions released in the storage and degradation phases (Reichalter et al., 2011). Production of methane in the anaerobic digestion plant replaces fossil fuels for electricity generation and therefore adds up to the energy savings.

*Conclusions*

The goals of this research were to understand the most important impacts related to milk production and potential ways to decrease impacts by means of more appropriate resource use and efficiency improvement. Two dairy farms (in Italy and Poland) were investigated and compared. Moreover, the benefits of energy self-generation were analysed by comparing the performances of the Italian farm before and after the introduction of self-generated electricity via photovoltaic modules and via combustion of biogas from manure anaerobic digestion. The impacts of the shift from manure to digestate use for fertilization purpose, as complement to chemical fertilization were also assessed.
The analysis showed that the transition from fossil energy use to energy self-sufficiency in the Italian farm improved several calculated indicators, in particular decreased the use of abiotic material resources and fossil energy use, respectively by 15% and 24%, while the contribution to GWP dropped by 37%. Acidification and Eutrophication decreased in a lower extent compared to GWP. The emergy indicators, such as the ELR and EYR, remained more or less the same due to the small role that

electricity plays among the other emergy input flows. In a way, the emergy assessment helps understand that energy is not the most important aspect in the milk production activity. While decreasing the fossil energy demand is certainly a contribution to decrease or prevent further climate changes, yet the global sustainability of the farm can only be achieved through a more balanced use of all other resources (e.g., better management of fertilization practices, and feedstock production), as well as through optimization of labor and services inputs.

The study highlights the critical aspects of the two dairy farms for a better redesign of the dairy farm activities and its relationship with the local and global environment as well as with the economic system interacting with these activities.

## D. *Decomposition Analysis and identification of major drivers of change.*

**INTRODUCTION**

In this work we have investigated the environmental and socio-economic sustainability of the agricultural systems of two Italian regions, Emilia Romagna in the Northern Italy, and Campania, in the South. These regional systems are characterized by different trends of climate, soil structure, mix of crops produced, agricultural practices (intensive, integrated, organic, biodynamic, etc) that affect production results and translate into different values of the indicators (emergy) and the drivers of change (decomposition). Due to these characteristics, these regional systems are representative of the variety of agricultural production patterns in Italy. The coexistence of different agricultural systems (northern versus southern, coastal versus inland, mountain versus plain, intensive versus subsistence, etc) is frequent in many countries, so that an evaluation approach capable to appreciate diversity and complexity would be a suitable tool for assessment and comparison worldwide.

The case study was performed by means of the emergy accounting method (Odum, 1996; Brown and Ulgiati, 2004a, b) coupled with a decomposition analysis technique (Vehmas, 2009). The latter was applied to a calculated time series of emergy indices and ratios in order not only to compare the two regional agricultural systems on the basis of their energy and emergy performances, but also with the purpose to ascertain which factors, in the investigated period, directly and indirectly affected the changes in imported (F) and non-renewable emergy use (N) and the increase of total emergy use (U). The choice of these indicators for the decomposition test was determined by the fact that they largely characterize the resource efficiency and sustainability of an agricultural system.

*The investigated Regional Agricultural Systems*

The agricultural sectors of Emilia Romagna and Campania regions were investigated over the time period 1985-2010. The Emilia Romagna region is situated in the central-northern part of Italy while Campania is located in the southern part. Figures 1.12a and 1.12b highlight the large fraction of agricultural area as well as a non-negligible fraction of forested and natural environment. Both regions are characterized by a mixed hilly and plain physical environment. They have a long lasting agricultural tradition characterized by high quality production of cereals such as soft and durum wheat (Fanfani R., 2001; Felice, 2011). A large fraction of the cropped areas in both Regions is dedicated to the cultivation of forage for livestock consumption. Emilia Romagna is also specialized in the cultivation of sugar beet, vineyard, peaches, nectarines and pears, while Campania excels in the production of olive, lemons, oranges, tomatoes and vineyard. Both Regions also have an important agro-food industry, the products of which are exported worldwide[7].

The agricultural productive structure of the Emilia Romagna region consists of farms characterized by an average size of 14.6 hectares, while the average farm size in the Campania region is about 4.0 hectares. In both Regions the average size is increasing over time because of the gradual expulsion of farmers from business due to the effects of European agricultural policies and market competition that lead to concentration of land into larger farms[8].

Nowadays intensive agriculture is the dominant productive farming pattern applied in the two Regions. Alternative productive farming systems such as organic and biodynamic, integrated pest management, account respectively for the 6.8% and 11.7% of Emilia Romagna cropped land, while it is 4.2% of total land in Campania. These alternative farming patterns are receiving increasing attention and financial support within the framework of rural development policies.

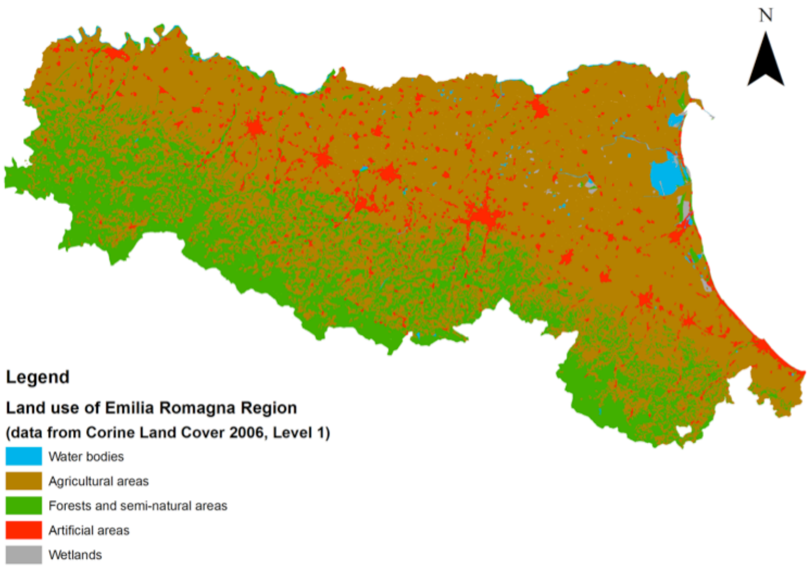


**Figure 1.12a.** Land cover map of Emilia Romagna Region (from Corinne Land Cover, 2006).

[7] Emilia Romagna Region, Invest in agro-food in Emilia Romagna, available: http://www.investinemiliaromagna.it/wcm/investiner_en/pagine/production_chain_sheets/Invest_in_Agrofood.pdf

Discovering Italian Regions, Emilia Romagna, available: http://www.italianflavours.org/articles/index/4cfd2bee-f2cc-455b-91a2-7e6d4548f53a

[8] http://agronotizie.imagelinenetwork.com/attualita/2011/07/07/istat-aziende-agricole-in-forte-calo-ma-piu-grandi/13643

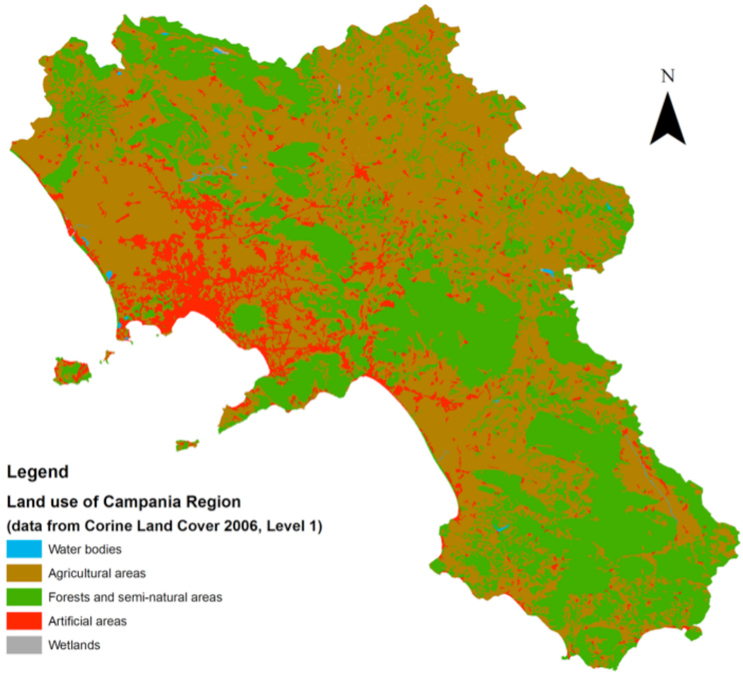


**Figure 1.12b**. Land cover map of Campania Region (from Corinne Land Cover, 2006).

*Data categories and quality*

The main input and output flows related to the annual regional crop production were collected from official statistical databases and personal interviews to dealers, farmers and managers. The output was quantified, for the purpose of the present assessment, as dry mass (g), energy content (J) and economic value (€; Gross Production Value, GPV[9]) of the total regional sector. In so doing it was possible to aggregate the products from a variety of crops into a total amount assumed as reference flow. The renewable input flows included in the account were solar radiation, wind, geothermal heat, rainfall, irrigation water, while the non-renewable flows were diesel, electricity, nitrogen (N), phosphate ($P_2O_5$) and potassium ($K_2O$) fertilizers, pesticides (fungicides, insecticides and herbicides), agricultural machinery (tractors, cultivators, combine harvesters, self-loading-trailers, round balers, grape harvesters, etc.) and human labor. The renewable input flows data came from the National Agrometeorological Database, CRA-CMA[10], the annual reports of National and Regional Institutes for

[9] Gross Production Value, GPV, is expressed in current prices (Euro). In the period covered by the study the inflation rate has been rather constant. Since current prices are usual in emergy analysis, current prices are used in this paper to make comparison easier.

[10] CRA-CMA,(2012) National Agrometeorologic Database. http://www.cra-cma.it/

Environmental Protection and Research ISPRA[11] and the National Environmental Agency ARPA[12]. Data about fertilizers pesticides and human labor (number of workers employed I agriculture and annual working hours) were taken from annual handbooks of the National Institute of Statistics, ISTAT[13] while data on fuels and machinery are available from the regional database of Mechanization in Agriculture, U.M.A.[14] Finally, data on residential population in both regions were taken from ISTAT historical time series.[15]

With regard to the output flows, the regional data of the annual crop production (wet matter) have been processed to yield the dry mass and the energy content of each crop, based on average energy content values from the database of the Italian National Institute for Research in Food and Nutrition, INRAN[16]. The economic value of annual crop production is accounted for as their Gross Production Value (GPV), calculated by the National Institute of Statistics, ISTAT[17].

Tables 1.10 and 1.11 provide examples of the calculation procedure. In Table 1.10 (Emilia Romagna region), the emergy supporting labor and services was splitted into its renewable and nonrenewable fractions, in order to understand how renewable labor and services could be considered. Since results show that they only account for a negligible share of renewable inputs, this splitting was not included in Table 1.11 (Campania).

*Decomposition Analysis Concepts and Procedure*

The decomposition analysis is widely used to investigate the impact of policies that address or regulate energy use (Ang and Zhang, 2000; European Commission, 2003; Ang, 2004; Jungnitz, 2008; Reddy and Ray, 2010; Sheinabum-Pardo *et al*., 2012), material consumption (Hoffrén *et al*., 2000; Hoffrén and Luukkanen, 2001; Jungnitz, 2008) and $CO_2$ emissions (Cialani, 2007; Jungnitz, 2008; Reddy and Ray, 2010; Sheinbaum-Pardo *et al*., 2012), as well as consequences of and linkages to societal

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11 ISPRA (2012)Annual reports on climatic indicators in Italy (years 2005 and 2010), available: http://www.isprambiente.gov.it/it/pubblicazioni/stato-dellambiente/gli-indicatori-del-clima-in-italia-nel-2010-anno

12 ARPA (2012), Hydrological Annals Report, http://www.arpa.emr.it/documenti.asp?parolachiave=sim_annali&cerca=si&idlivello=64&pag=2

13 ISTAT, Agricultural statistics, available: http://agri.istat.it

14 UMA (2012), Utenti Motori Agricoli, available: http://www.ucer.camcom.it/studi-ricerche/banche-dati/bd/agricolt/uma

15 ISTAT, Residential population in Emilia Romagna Region and Campania Region, http://seriestoriche.istat.it/index.php?id=7&user_100ind_pi1[id_pagina]=44&cHash=b58adf960212bedd42e9fa9d2f2765a7

16 INRAN (2012), National institute for Research in Food and Nutrition, nutritional tables available: http://www.inran.it/646/tabelle_di_composizione_degli_alimenti.html

17 ISTAT (2012), Gross Production Value (GPV), available: http://www.istat.it/it/archivio/1654

phenomena such as population increase, ageing, land use. Since the decomposition analysis is able to assess the ability of a given parameter or use change or policy to affect the final result, it can considered a very important tool to ease the monitoring and evaluation of the sustainability of whole economies and productive structures (Hoffrén *et al.*, 2000). The knowledge of the factors that affect the process performance is essential for the design of new policy instruments and the evaluation of the implemented measures (Jungnitz, 2008) over a desired sustainability pattern.

The decomposition analysis carried out in this study is an Index Decomposition Analysis (Ang, 2004), based on the Advanced Sustainability Analysis (ASA) tool (Luukkanen and Malaska, 2001; Malaska and Luukkanen, 2001; DECOIN, 2007; Vehmas, 2009; SMILE, 2011). ASA is a mathematical and software data processing system developed by Finland Futures Research Centre, designed to point out relationships between changes in environmental, economic and social variables that are measured by any preferred indicator or index. According with the ASA method, the decomposition analysis calculates the effect/contribution of each "explaining" factor and their "joint impact", which in a complete decomposition must be allocated to the explaining factors.

An equation for describing the relationship between the factors (intensive factor V/X1 and extensive factor X1) contributing to a variable V can be expressed in its simplest form as follows (Equation 5):

$$V = \frac{V}{X1} X1 \qquad \text{Eqn. (5)}$$

This kind of analysis can be applied to multiple explaining factors as well. The two-factor decomposition presented in Equation (5) can be expanded by taking the result from the first decomposition as a starting point for further decompositions, and the new results can then be decomposed again. The equation which identifies the contributing variables can be formulated in a general form as follows (Equation 6):

$$V = \frac{X1}{X2} \times \frac{X2}{X3} \times \ldots . \times \frac{Xn-1}{Xn} \times Xn \; (n \geq 2) \qquad \text{Eqn. (6)}$$

The pre-requisite for the application of the technique is the availability of a suitable time series of data and performance indicators. A more detailed explanation of the ASA approach and its underlying mathematical procedures can be found in the cited literature.

## RESULTS

### *Input and output flows data characteristics*

Our study only focuses on crop production (livestock and multifunctional activities are not included). In 2010 the cropped land was 1.07 million hectares in Emilia

Romagna and 0.5 million hectares in Campania. Statistical data from Agricultural Census 2010 (ISTAT, 2010) show the gradual decrease of the cropped land over time in both regions. In particular, from 1985 to 2010 the cropped land decreased by 14% in Emilia Romagna and by 47% in Campania (Figure 1.13). The abandonment of rural areas and the land use change in favor of urbanization, transport and industrial infrastructure have common causes in all Italian Regions: decreasing farmers' income, population ageing, reduction of the number of farms, lack of turnover between generations, social and cultural aspects (WWF, 2012). In some Regions, including Campania, rural activities have also been affected by aggressive and sometimes illegal expansion of built environment (Mazzeo, 2009; WWF, 2012).

This phenomenon has many implications, as it reduces the capacity to satisfy the growing food demand, increases the vulnerability of the territories and reduces the future opportunities for human activities and sustainable business (Rabboni, 2012).

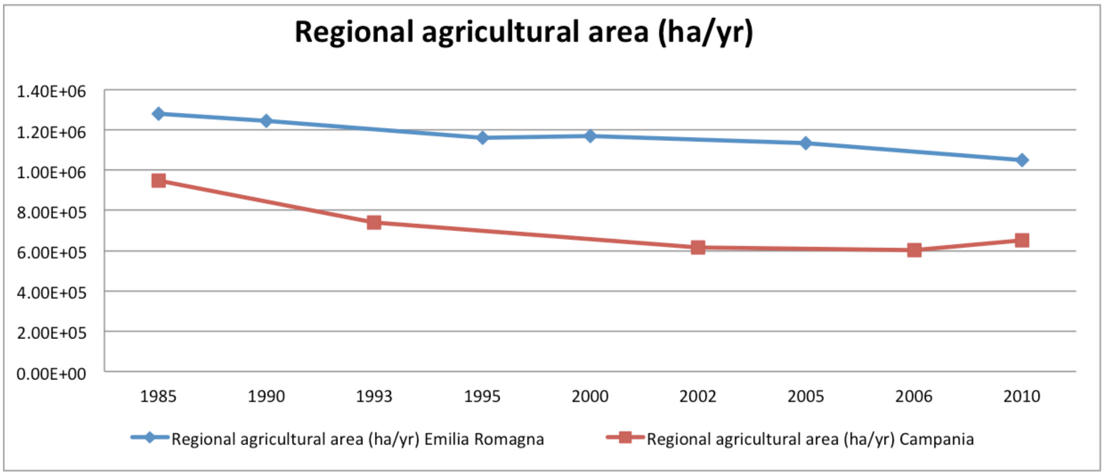


**Figure 1.13**. Cropped land (ha/year) in Emilia Romagna and Campania agricultural systems in the investigated period.

Figures 1.14a and 1.14b show a declining production trend in both regions (much more evident in Campania), while instead the current price GPV increased up to the year 2000 and then stabilized with small oscillations. The crop production of Emilia Romagna Region declines from the 14.6 million of d.m. tons in the year 1985 and the 13.2 million tons in the year 2010, while Campania Region production decreases from the 5.3 million of d.m. tons in 1985 to 4.9 million of tons of 2010. In Emilia Romagna the production decrease is the result of a constant and slightly oscillating decline of land cropped with temporary forage, soft wheat and sugar beet. In 2010 compared to 1985, the sugar beet recorded the highest reductions of its cropped land share (-73.6%), followed by barley (-53.3%), soft wheat (-41.9%) and vineyard (-30.6%), while maize (+117.4%), tomatoes (+81.9%) and durum wheat (+57.1%) show an increasing trend. In Campania the reduction is mainly related to the decrease of agricultural land (as mentioned above, from 1985 to 2010 such decrease was 47%).

However, the total and per hectare yield in Emilia Romagna are always much higher than for Campania (averaging respectively 2.6 and 1.6 times). This trade-off between intensification and yield is exactly the problem that must be faced in policy-making, namely a balance between environmental and economic sustainability.

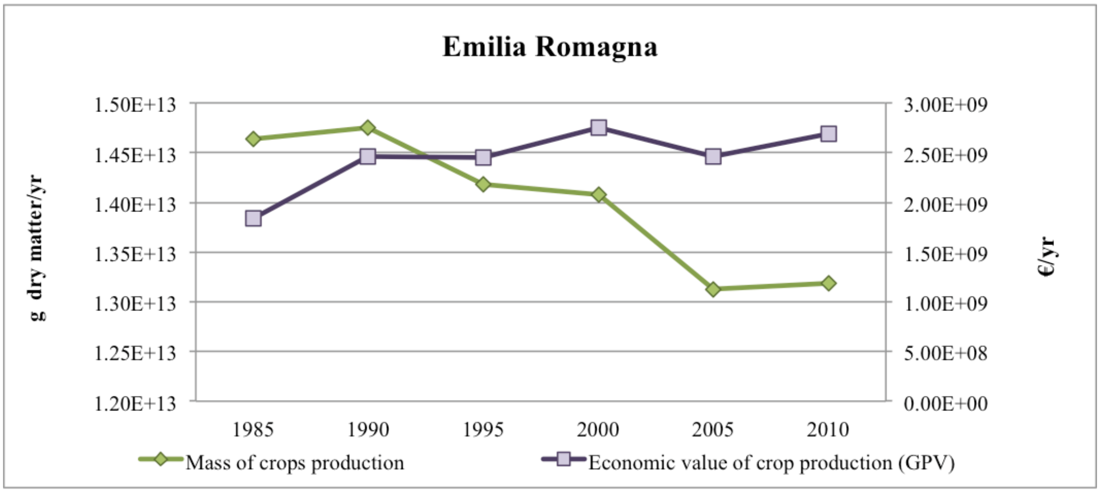


**Figure 1.14a.** Evolution of the mass of crop production (left axis) and economic value of crop production (GPV) (right axis) in Emilia Romagna region.

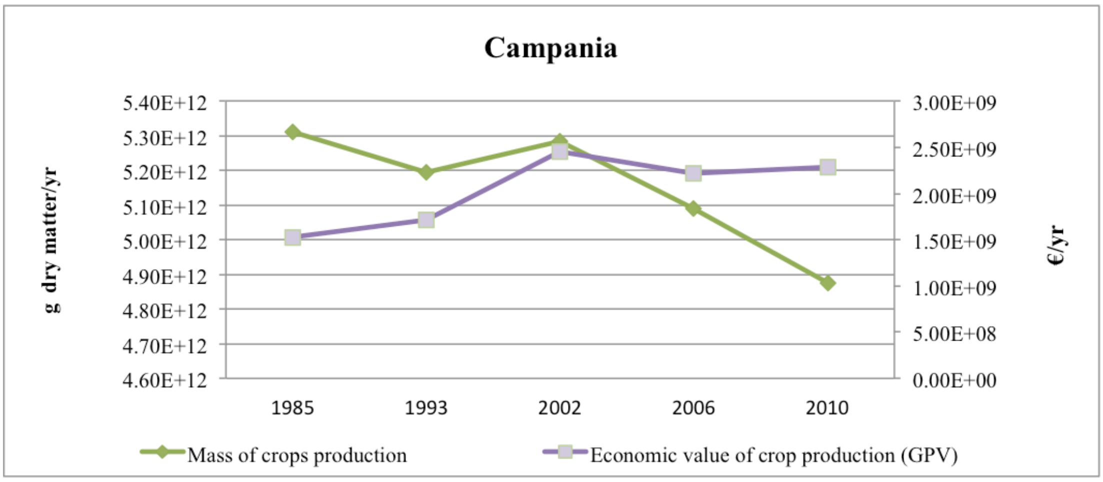


**Figure 1.14b.** Evolution of the mass of crop production (left axis) and economic value of crop production (GPV) (right axis) in Campania region.

Consistently with the characteristics of other industrialized regions, the present contribution of the agricultural sector (Agricultural Gross Domestic Product share) to the total regional Gross Domestic Product (RGDP) is marginal (2.1% in 2009 in Emilia Romagna and 2.2% in 2009 in Campania) compared to the industry and service sectors. Furthermore, the traditional agricultural activities (crops and livestock production) account for the highest contribution to the agricultural regional Gross Production Value compared to the present contribution from multifunctional activities (agritourism, energy production, handicraft products, production of animal feed, etc), the share of which in 2010 amounted to a low 10.3% for Emilia Romagna and 9.6% for Campania.

*Resource flows supporting the two agricultural systems of Campania and Emilia Romagna*

The main input flows supporting the two investigated agricultural systems in the year 2010 are listed in Tables 1.12 and 1.13. Inputs are divided into Renewable, Nonrenewable, Imported and Economic categories. The economic category includes direct labor as well as services (indirect labor performed outside the system boundary to process and delivers the imported input resources). In both regional agricultural systems human labor and services accounted for about 50% of the total emergy flow, U, thus indicating a very labor-intensive agro-industrial sector. Table 1.12 shows, in the first three columns, the main input flows supporting the regional agriculture of Emilia Romagna in the year 2010. The third column refers to the raw amounts of input collected; these raw amounts are multiplied by a suitable conversion factor (UEV) indicated in the fourth column to yield the emergy associated to each input flow. Economic flows of labor and services (L&S) are also indicated and two emergy totals are drawn, with and without inclusion of L&S. The relative (%) importance of each flow compared to the total emergy used (with and without L&S) was also calculated. Rainfall (9% and 21% with/without L&S), agricultural diesel (9% and 21% with/without L&S), electricity (5% and 12% with/without L&S), water for irrigation (9% and 21% with/without L&S) and fertilizers (6% and 16% with/without L&S) and Labor (22%) and Services (33%) gave the largest contributions to the total emergy U. The dominance of services (33%) should not be disregarded, since it indicates the dependence of the agricultural sector demand for resources on the performance and efficiency of the upstream industrial and infrastructure sectors that supply goods and opportunities to agriculture.

**Table 1.12. Emergy evaluation of Emilia Romagna agriculture in 2010.**

| Items | Units | Raw amount | UEV (seJ/unit) | Refs for UEVs | Emergy (seJ/yr) | % of Total Emergy (*) | % of Total Emergy (**) |
|---|---|---|---|---|---|---|---|
| **Renewable Input (locally available)** | | | | | | | |
| Sun | J/yr | 4.25E+19 | 1 | [a] | 4.25E+19 | 1% | 1% |
| Wind (kinetic energy of wind used at the surface) | J/yr | 1.08E+17 | 2.51E+03 | [b] | 2.71E+20 | 3% | 6% |
| Rainfall (chemical potential) | J/yr | 2.64E+16 | 3.05E+04 | [b] | 8.06E+20 | 10% | 18% |
| Deep Heat (Geothermal) | J/yr | 1.52E+16 | 1.20E+04 | [b] | 1.83E+20 | 2% | 4% |
| Services, renewable fraction | €/yr | 5.19E+07 | 2.75E+12 | [h] | 1.43E+20 | 2% | |
| Labor, renewable fraction | €/yr | 3.37E+07 | 2.75E+12 | [h] | 9.27E+19 | 1% | |
| **Nonrenewable Input (locally available)** | | | | | | | |
| Top soil (erosion, weathering) | J/yr | 2.31E+14 | 1.24E+05 | [b] | 2.85E+19 | 0% | 1% |
| **Imported Input** | | | | | | | |
| Gasoline | J/yr | 4.71E+13 | 1.11E+05 | [b] | 5.22E+18 | 0% | 0% |
| Diesel | J/yr | 8.85E+15 | 1.11E+05 | [b] | 9.79E+20 | 12% | 22% |
| Electricity | J/yr | 1.93E+15 | 2.81E+05 | [c] | 5.41E+20 | 6% | 12% |
| Water for irrigation | g/yr | 1.28E+15 | 7.61E+05 | [d] | 9.73E+20 | 12% | 22% |
| Fertilizers | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *Nitrogen (N)* | g/yr | 6.20E+10 | 6.37E+09 | [b] | 3.95E+20 | 5% | 9% |
| *Phosphate (P2O5)* | g/yr | 4.25E+10 | 6.54E+09 | [b] | 2.78E+20 | 3% | 6% |
| *Potassium (K2O)* | g/yr | 2.07E+10 | 1.84E+09 | [b] | 3.82E+19 | 0% | 1% |
| Fungicides | g/yr | 5.03E+09 | 5.08E+09 | [e] | 2.56E+19 | 0% | 1% |
| Insecticides and Acaricides | g/yr | 1.57E+09 | 4.81E+09 | [e] | 7.57E+18 | 0% | 0% |
| Herbicides | g/yr | 1.52E+09 | 8.25E+09 | [e] | 1.25E+19 | 0% | 0% |
| Machinery | | | | | | | |
| *steel and iron* | g/yr | 2.34E+10 | 5.31E+09 | [f] | 1.24E+20 | 1% | 3% |
| *aluminium* | g/yr | 3.99E+09 | 3.25E+10 | [b] | 1.30E+20 | 2% | 3% |
| *rubber and plastic material* | g/yr | 2.85E+08 | 3.69E+09 | [g] | 1.05E+18 | 0% | 0% |
| *copper* | g/yr | 8.54E+08 | 3.36E+09 | [c] | 2.87E+18 | 0% | 0% |
| Seeds | g/yr | 6.47E+10 | 1.67E+09 | [i] | 1.08E+20 | 1% | 2% |
| Labor, non-renewable fraction | €/yr | 5.28E+08 | 2.75E+12 | [h] | 1.45E+21 | 17% | |
| Services, non-renewable fraction | €/yr | 8.13E+08 | 2.75E+12 | [h] | 2.24E+21 | 27% | |
| **TOTAL EMERGY (with Labor and Services)** | | | | | **8.38E+21** | 100% | 100% |
| **TOTAL EMERGY (without Labor and Services)** | | | | | **4.45E+21** | | |

(*) calculated with reference to total emergy U, including Labor and Services

(**) calculated with reference to total emergy U, without inclusion of Labor and Services

In a like manner, Table 1.13 lists the most relevant emergy inputs supporting Campania agriculture. The main renewable, imported and economic flows are respectively rainfall (13% and 27% with/without L&S), agricultural diesel (11% and 23% with/without L&S), electricity (7% and 14% with/without L&S) and fertilizers (8% and 16% with/without L&S). Direct labor accounts for 22% and services account for 28% of total emergy use in the region.

**Table 1.13. Emergy evaluation of Campania agriculture in 2010.**

| Items | Units | Raw amount | UEV (seJ/unit) | Refs. UEV | Emergy (seJ/yr) | % of Total Emergy (*) | % of Total Emergy (**) |
|---|---|---|---|---|---|---|---|
| **Renewable Input (locally available)** | | | | | | | |
| Sun | J/yr | 3.05E+19 | 1.00E+00 | [a] | 3.05E+19 | 1% | 2% |
| Wind | J/yr | 6.08E+16 | 2.51E+03 | [b] | 1.52E+20 | 3% | 8% |
| Rainfall | J/yr | 1.88E+16 | 3.05E+04 | [b] | 5.72E+20 | 12% | 30% |
| Deep Heat | J/yr | 8.46E+15 | 1.20E+04 | [b] | 1.01E+20 | 2% | 5% |
| **Nonrenewable Input (locally available)** | | | | | | | |
| Top soil (erosion, weathering) | J/yr | 8.59E+14 | 1.24E+05 | [b] | 1.06E+20 | 2% | 6% |
| **Imported Input** | | | | | | | |
| Gasoline | J/yr | 0.00E+00 | 1.11E+05 | [b] | 0.00E+00 | 0% | 0% |
| Diesel and heavy fuel | J/yr | 4.08E+15 | 1.11E+05 | [b] | 4.51E+20 | 9% | 24% |
| Electricity | J/yr | 9.77E+14 | 2.81E+05 | [c] | 2.74E+20 | 6% | 14% |
| Water for irrigation | g/yr | 9.37E+13 | 7.61E+05 | [d] | 7.13E+19 | 1% | 4% |
| Fertilizers | | | | | | | |
| *Nitrogen (N)* | g/yr | 4.44E+10 | 6.37E+09 | [b] | 2.83E+20 | 6% | 15% |
| *Phosphate (PO4)* | g/yr | 5.61E+09 | 6.54E+09 | [b] | 3.66E+19 | 1% | 2% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *Potassium (K2O)* | g/yr | 6.22E+08 | 1.84E+09 | [b] | 1.15E+18 | 0% | 0% |
| Fungicides | g/yr | 3.61E+09 | 5.08E+09 | [e] | 1.84E+19 | 0% | 1% |
| Insecticides and Acaricides | g/yr | 2.01E+09 | 4.81E+09 | [e] | 9.65E+18 | 0% | 1% |
| Herbicides | g/yr | 1.09E+09 | 8.25E+09 | [e] | 9.02E+18 | 0% | 0% |
| Agricultural machinery | | | | | | | |
| *steel and iron* | g/yr | 6.77E+09 | 5.31E+09 | [f] | 3.59E+19 | 1% | 2% |
| *aluminium* | g/yr | 1.16E+09 | 3.25E+10 | [b] | 3.76E+19 | 1% | 2% |
| *rubber and plastic material* | g/yr | 8.25E+07 | 3.69E+09 | [g] | 3.04E+17 | 0% | 0% |
| *copper* | g/yr | 2.48E+08 | 3.36E+09 | [c] | 8.32E+17 | 0% | 0% |
| Human Labor | €/yr | 6.43E+08 | 2.75E+12 | [h] | 1.77E+21 | 37% | |
| Services | €/yr | 4.10E+08 | 2.75E+12 | [h] | 1.13E+21 | 23% | |
| **TOTAL EMERGY (with Labor and Services)** | | | | | **4.70E+21** | 100% | 100% |
| **TOTAL EMERGY (without Labor and Services)** | | | | | **1.80E+21** | | |

(*) calculated with reference to total emergy U, including Labor and Services
(**) calculated with reference to total emergy U, without inclusion of Labor and Services

Tables 1.14 and 1.15 list the calculated values of the main emergy indicators for the two agricultural systems. Indicators are grouped into two categories, intensive and extensive, calculated with and without including L&S. The total emergy (U) supporting the annual crop production is relatively stable in both regions: in Emilia Romagna U is about twice the value of Campania, in all years.

**Table 1.14. Intensive and extensive indicators of Emilia Romagna agriculture over time.**

| Indicators | Unit | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|
| ***Intensive Indicators with L&S*** | | | | | | | |
| Emergy intensity per GVP | seJ/€ | 4.36E+12 | 3.28E+12 | 3.43E+12 | 2.79E+12 | 3.30E+12 | 3.11E+12 |
| Empower density | seJ/ha | 6.26E+15 | 6.50E+15 | 7.23E+15 | 6.55E+15 | 7.02E+15 | 7.98E+15 |
| Emergy intensity per g d.m. | seJ/g d.m. | 5.47E+08 | 5.48E+08 | 5.93E+08 | 5.45E+08 | 6.20E+08 | 6.35E+08 |
| Transformity | sej/J | 3.36E+04 | 3.37E+04 | 3.64E+04 | 3.34E+04 | 3.79E+04 | 3.88E+04 |
| EYR = U/(F+L+S) | | 1.15 | 1.14 | 1.13 | 1.13 | 1.13 | 1.15 |
| EIR = 1/(EYR-1) | | 6.65 | 7.35 | 7.98 | 7.43 | 7.47 | 6.83 |
| ELR = (N+F+S)/R | | 6.91 | 7.65 | 8.30 | 7.73 | 7.76 | 7.05 |
| %REN = 1/(1+ELR) | | 0.13 | 0.12 | 0.11 | 0.11 | 0.11 | 0.12 |
| ESI = EYR/ELR | | 0.17 | 0.15 | 0.14 | 0.15 | 0.15 | 0.16 |
| ***Intensive Indicators without L&S*** | | | | | | | |
| Emergy intensity per GVP | seJ/€ | 2.39E+12 | 1.84E+12 | 1.87E+12 | 1.58E+12 | 1.89E+12 | 1.65E+12 |
| Empower density | seJ/ha | 3.43E+15 | 3.65E+15 | 3.94E+15 | 3.72E+15 | 4.02E+15 | 4.24E+15 |
| Emergy intensity per g d.m. | seJ/g d.m. | 3.00E+08 | 3.07E+08 | 3.23E+08 | 3.09E+08 | 3.55E+08 | 3.38E+08 |
| Transformity | sej/J | 1.84E+04 | 1.89E+04 | 1.98E+04 | 1.90E+04 | 2.17E+04 | 2.06E+04 |
| EYR = U*/F | | 1.23 | 1.20 | 1.18 | 1.20 | 1.19 | 1.23 |
| EIR = 1/(EYR-1) | | 4.29 | 5.00 | 5.48 | 5.12 | 5.20 | 4.34 |
| ELR = (N+F)/L | | 4.52 | 5.28 | 5.79 | 5.40 | 5.47 | 4.53 |
| %REN = 1/(1+ELR) | | 0.18 | 0.16 | 0.15 | 0.16 | 0.15 | 0.18 |
| ESI = EYR/ELR | | 0.27 | 0.23 | 0.20 | 0.22 | 0.22 | 0.27 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ***Extensive Indicators*** | | | | | | | |
| Renewable inputs, R (without double counting) | seJ/yr | 7.96E+20 | 7.21E+20 | 6.74E+20 | 6.79E+20 | 7.20E+20 | 8.06E+20 |
| Renewable inputs, R (without double counting, including Ren. Fraction of L.&S.) | seJ/yr | 1.01E+21 | 9.34E+20 | 9.04E+20 | 8.78E+20 | 9.29E+20 | 1.04E+21 |
| Locally nonrenewable inputs, N | seJ/yr | 3.48E+19 | 3.38E+19 | 3.16E+19 | 3.18E+19 | 3.15E+19 | 2.85E+19 |
| Purchased inputs, F (without L&S) | seJ/yr | 3.57E+21 | 3.78E+21 | 3.87E+21 | 3.64E+21 | 3.91E+21 | 3.62E+21 |
| Direct Labor, L, non renewable | seJ/yr | 1.88E+21 | 1.89E+21 | 2.02E+21 | 1.54E+21 | 1.34E+21 | 1.45E+21 |
| Services (non-ren fraction) | seJ/yr | 1.52E+21 | 1.45E+21 | 1.58E+21 | 1.58E+21 | 1.92E+21 | 2.24E+21 |
| Total emergy, U= (R+N+F+L+S) | seJ/yr | 8.01E+21 | 8.08E+21 | 8.40E+21 | 7.67E+21 | 8.14E+21 | 8.38E+21 |
| Total emergy, U*= (R+N+F) | seJ/yr | 4.40E+21 | 4.53E+21 | 4.58E+21 | 4.35E+21 | 4.66E+21 | 4.45E+21 |
| **Indicators** | **Unit** | **1985** | **1990** | **1995** | **2000** | **2005** | **2010** |

**Table 1.15. Intensive and extensive indicators of Campania agriculture over time.**

| Indicators | Unit | 1985 | 1993 | 2002 | 2006 | 2010 |
|---|---|---|---|---|---|---|
| ***Intensive Indicators with L&S*** | | | | | | |
| Emergy intensity per GPV | seJ/€ | 3.44E+12 | 2.72E+12 | 2.04E+12 | 2.31E+12 | 2.10E+12 |
| Empower density | seJ/ha | 5.55E+15 | 6.30E+15 | 8.17E+15 | 8.51E+15 | 7.37E+15 |
| Emergy intensity per g d.m. | seJ/g d.m. | 9.92E+08 | 9.00E+08 | 9.52E+08 | 1.01E+09 | 9.84E+08 |
| Transformity | sej/J | 6.22E+04 | 5.53E+04 | 5.89E+04 | 6.42E+04 | 5.86E+04 |
| EYR = U/(F+L+S) | | 1.16 | 1.13 | 1.11 | 1.10 | 1.16 |
| EIR = 1/(EYR-1) | | 6.42 | 7.92 | 9.46 | 10.25 | 6.08 |
| ELR = (N+F+S)/R | | 7.37 | 9.14 | 10.74 | 11.68 | 7.39 |
| %REN = 1/(1+ELR) | | 0.12 | 0.10 | 0.09 | 0.08 | 0.12 |
| ESI = EYR/ELR | | 0.16 | 0.12 | 0.10 | 0.09 | 0.16 |
| ***Intensive Indicators without L&S*** | | | | | | |
| Emergy intensity per GPV | seJ/€ | 1.55E+12 | 1.22E+12 | 8.46E+11 | 9.27E+11 | 8.34E+11 |
| Empower density | seJ/ha | 2.50E+15 | 2.83E+15 | 3.38E+15 | 3.41E+15 | 2.93E+15 |
| Emergy intensity per g d.m. | seJ/g d.m. | 4.47E+08 | 4.05E+08 | 3.94E+08 | 4.04E+08 | 3.91E+08 |
| Transformity | sej/J | 2.80E+04 | 2.48E+04 | 2.44E+04 | 2.58E+04 | 2.33E+04 |
| EYR = U*/F | | 1.43 | 1.33 | 1.30 | 1.28 | 1.55 |
| EIR = 1/(EYR-1) | | 2.34 | 3.01 | 3.33 | 3.52 | 1.81 |
| ELR = (N+F)/L | | 2.77 | 3.56 | 3.86 | 4.09 | 2.33 |
| %REN = 1/(1+ELR) | | 0.27 | 0.22 | 0.21 | 0.20 | 0.30 |
| ESI = EYR/ELR | | 0.51 | 0.37 | 0.34 | 0.31 | 0.67 |
| ***Extensive Indicators*** | | | | | | |
| Locally renewable inputs, R | seJ/yr | 6.29E+20 | 4.61E+20 | 4.28E+20 | 4.05E+20 | 5.72E+20 |
| Locally nonrenewable inputs, N | seJ/yr | 8.05E+19 | 6.29E+19 | 5.22E+19 | 5.11E+19 | 1.06E+20 |
| Purchased inputs, F | seJ/yr | 1.66E+21 | 1.58E+21 | 1.60E+21 | 1.60E+21 | 1.23E+21 |
| Direct Labor, L, non renewable | seJ/yr | 2.05E+21 | 1.73E+21 | 2.07E+21 | 1.90E+21 | 1.77E+21 |
| Indirect labor (services), non renewable | seJ/yr | 8.49E+20 | 8.43E+20 | 8.80E+20 | 1.17E+21 | 1.13E+21 |
| Total Emergy U= (R+N+F+L+S) | seJ/yr | 5.27E+21 | 4.67E+21 | 5.03E+21 | 5.13E+21 | 4.80E+21 |
| Total Emergy U*= (R+N+F) | seJ/yr | 2.37E+21 | 2.10E+21 | 2.08E+21 | 2.06E+21 | 1.91E+21 |

It is very telling to analyze the breakdown and the trends of raw emergy flows. In order to be able to identify also the smaller flows we did not include in the breakdown the emergy of human labor and services (being very large flows, they hides the smaller inputs). Moreover, Labor and Services are strictly correlated to the dynamics of the societal economy (the emergy "cost" of labor depends on the development level of a society) while instead we are also interested in the differences of the agricultural production process as such (i.e. trend of resource use, mix of crops, climate, soil quality, yield). Figures 1.15a and 1.15b show the relative importance and time trends of emergy inputs (aggregated into main categories) compared to the total raw emergy use (= 100%). We can see that for both Emilia Romagna and Campania systems, renewables R have not a high share of total emergy use U and show a declining trend, except in the most recent years. The larger 2010 shares were Services (respectively 28% and 24% in Emilia Romagna and Campania, with an increasing trend) and Labor (18% in E.R. and 38% in Campania, gradually decreasing). Direct energy (fossil fuels) increase until recently and then decline. Agrochemicals show a gradual decline over time. Slow-renewables show a large share of emergy use in Emilia Romagna, mainly due to underground and aqueduct irrigation water, while slow-renewable topsoil erosion contributes to this category of resources in Campania region.

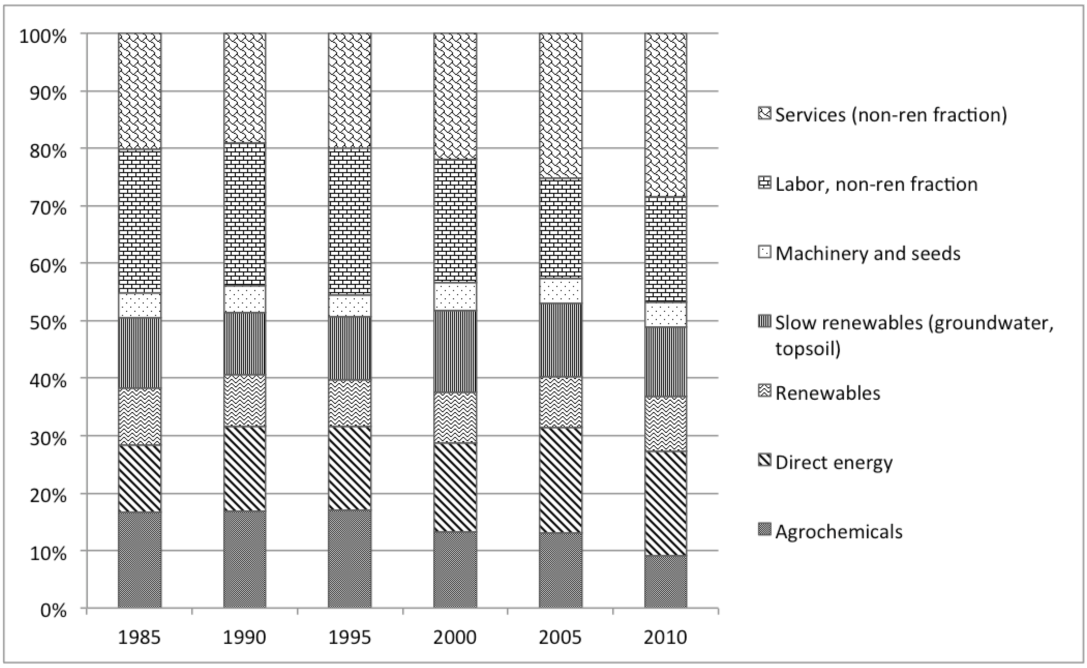


**Figure 1.15a.** Breakdown of emergy input to the Emilia Romagna agricultural system.

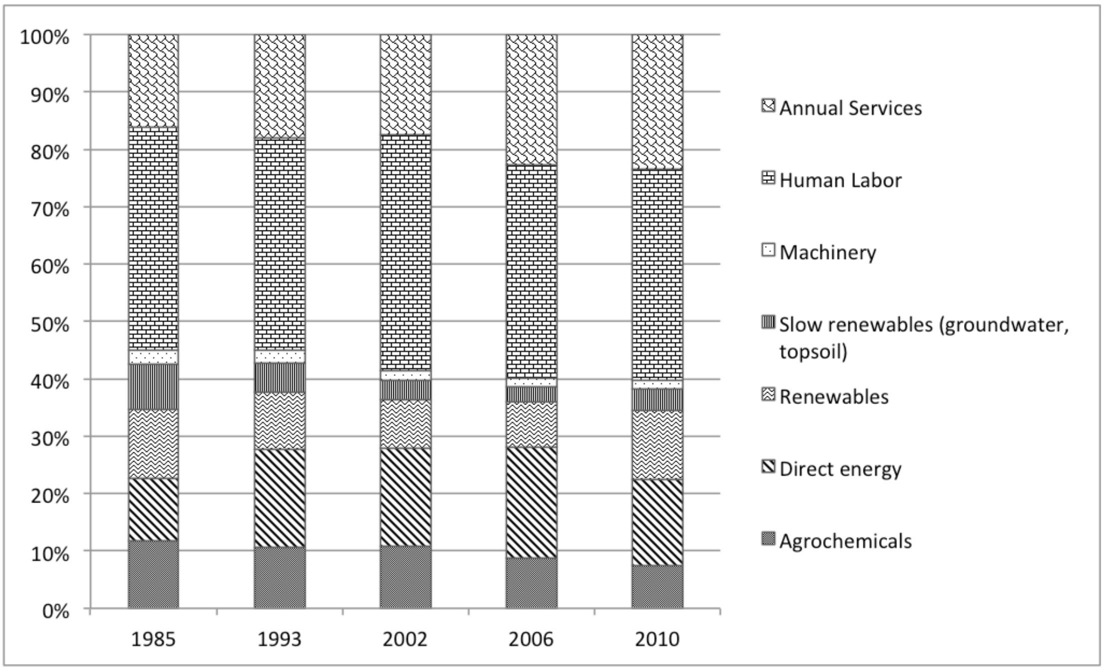


**Figure 1.15b.** Breakdown of emergy input to the Campania agricultural system.

*Decomposition of total emergy U*

The time changes of the amount of total emergy flow (U) were decomposed to understand the main drivers of change, based on data from Tables 1.14 and 1.15, by means of the Advanced Sustainability Analysis (ASA) approach described in Material and Methods. According to Equation (7), the change of total emergy U between the reference year $T_o$ (beginning of the considered period, 1985) and the end year $T_1$, can be decomposed into several driving component (or contributing) factors:

$$U= (U/F)*[F/(R+N)]*[(R+N)/AA]*(AA/POP)*(POP/Labor)*(Labor/GPV)*GPV \qquad \text{Eqn. (7)}$$

where (U/F) is the Emergy Yield Ratio EYR; F/(R+N) is the Investment Ratio EIR; (R+N)/AA[18] is the local Empower Density, $ED_L$ (a measure of carrying capacity based on locally available resources, renewable or not, seJ/ha), AA/POP[19] is agricultural land availability (hectares/person); POP/Labor is the people supported by a unit of agricultural labor (people/working hour); GPV is the Gross Production Value; Labor/GPV is time invested per unit of agricultural economic product (working hours/€).

Eqn. (5) clearly shows U to be linearly dependent on GPV trend, all other factors remaining the same. Instead, changes in the other driving factors introduce non-linearity aspects that need to be carefully taken into account.

[18] AA, agricultural area

[19] POP, residential population in the regions

Tables 1.16 and 1.17 show the time evolution of flows characterizing the two regional agricultural systems and the percentage of changes determined by each factor, relative to the year 1985.

Table 1.16. Trends of characterizing flows and driving factors in Emilia Romagna agriculture 1985-2010, with reference to the year 1985.

| **Flows (units)** | **1985** | **1990** | **1995** | **2000** | **2005** | **2010** |
|---|---|---|---|---|---|---|
| U (seJ/yr) | 8.01E+21 | 8.08E+21 | 8.40E+21 | 7.67E+21 | 8.14E+21 | 8.38E+21 |
| F (seJ/yr) | 3.57E+21 | 3.78E+21 | 3.87E+21 | 3.64E+21 | 3.91E+21 | 3.62E+21 |
| R+N (seJ/yr) | 8.31E+20 | 7.55E+20 | 7.06E+20 | 7.11E+20 | 7.52E+20 | 8.34E+20 |
| AA (ha) | 1.28E+06 | 1.24E+06 | 1.16E+06 | 1.17E+06 | 1.16E+06 | 1.05E+06 |
| POP (person) | 3.93E+06 | 3.90E+06 | 3.89E+06 | 3.95E+06 | 4.15E+06 | 4.38E+06 |
| Labor (hr/yr) | 1.43E+08 | 1.29E+08 | 9.77E+07 | 7.58E+07 | 6.07E+07 | 5.94E+07 |
| GVP (€/yr) | 1.84E+09 | 2.46E+0<br>9 | 2.45E+0<br>9 | 2.75E+0<br>9 | 2.46E+0<br>9 | 2.69E+0<br>9 |
| **Trend of driving factors** | **1985** | **1990** | **1995** | **2000** | **2005** | **2010** |
| U/F | 2.25 | 2.14 | 2.17 | 2.11 | 2.08 | 2.31 |
| F/(R+N) | 4.29 | 5.00 | 5.48 | 5.12 | 5.20 | 4.34 |
| (R+N)/AA (seJ/ha) | 6.49E+14 | 6.07E+14 | 6.07E+14 | 6.07E+14 | 6.49E+14 | 7.95E+14 |
| AA/POP (ha/population) | 0.33 | 0.32 | 0.30 | 0.30 | 0.28 | 0.24 |
| POP/Labor (population/work hrs) | 0.03 | 0.03 | 0.04 | 0.05 | 0.07 | 0.07 |
| Labor/GVP (work hrs/€) | 0.08 | 0.05 | 0.04 | 0.03 | 0.02 | 0.02 |
| GVP (€/yr) | 1.84E+09 | 2.46E+09 | 2.45E+09 | 2.75E+09 | 2.46E+09 | 2.69E+09 |
| **% Contribution to change of total U** | **1985** | **1985-1990** | **1985-1995** | **1985-2000** | **1985-2005** | **1985-2010** |
| U/F | 0.00 | -4.92 | -3.53 | -6.25 | -7.77 | 3.03 |
| F/(R+N) | 0.00 | 15.44 | 25.27 | 17.31 | 19.44 | 1.15 |
| (R+N)/AA | 0.00 | -6.65 | -6.82 | -6.49 | 0.00 | 20.88 |
| AA/POP | 0.00 | -2.33 | -9.14 | -9.29 | -15.75 | -31.76 |
| POP/Labor | 0.00 | 9.72 | 39.34 | 67.03 | 104.75 | 117.13 |
| Labor/GVP | 0.00 | -40.57 | -72.25 | -114.32 | -137.74 | -159.83 |
| GVP | 0.00 | 30.18 | 32.06 | 47.74 | 38.63 | 54.00 |

Tables 1.16 and 1.17 are divided into three sections. In the first one, the absolute values of selected parameters characterizing the system over time are shown (emergy flows, cropped land, regional population to be fed, working time applied, economic product). Important, in this section, the total emergy U= (R+N+F+L+S): in Emilia Romagna region U slightly increases over time (Table 1.16), while instead it decreases in Campania region (Table 1.17), after some oscillations in both regions. In the second section, selected performance ratios are calculated. Finally, the third section shows the percentage of positive or negative contribution of each performance ratio to the value of total emergy use U in each year.

Table 1.17. Trends of characterizing flows and driving factors in Campania agriculture 1985-2010, with reference to the year 1985.

| Flows (units) | 1985 | 1993 | 2002 | 2006 | 2010 |
|---|---|---|---|---|---|
| U (seJ/yr) | 5.27E+21 | 4.67E+21 | 5.03E+21 | 5.13E+21 | 4.80E+21 |
| F (seJ/yr) | 1.66E+21 | 1.58E+21 | 1.60E+21 | 1.60E+21 | 1.23E+21 |
| R+N (seJ/yr) | 7.10E+20 | 5.24E+20 | 4.81E+20 | 4.56E+20 | 6.78E+20 |
| AA (ha) | 9.49E+05 | 7.42E+05 | 6.15E+05 | 6.03E+05 | 6.51E+05 |
| POP (person) | 5.53E+06 | 5.66E+06 | 5.70E+06 | 5.79E+06 | 5.82E+06 |
| Labor (hr/yr) | 1.46E+08 | 1.11E+08 | 8.93E+07 | 8.10E+07 | 6.79E+07 |
| GVP (€/yr) | 1.53E+09 | 1.72E+09 | 2.46E+09 | 2.22E+09 | 2.29E+09 |
| **Trend of driving factors** | **1985** | **1990** | **1995** | **2000** | **2005** |
| U/F | 3.17 | 2.96 | 3.14 | 3.20 | 3.91 |
| F/(R+N) | 2.34 | 3.01 | 3.33 | 3.52 | 1.81 |
| (R+N)/AA (seJ/ha) | 7.48E+14 | 7.06E+14 | 7.81E+14 | 7.56E+14 | 1.04E+15 |
| AA/POP (ha/population) | 0.17 | 0.13 | 0.11 | 0.10 | 0.11 |
| POP/Labor (population/work hrs) | 0.04 | 0.05 | 0.06 | 0.07 | 0.09 |
| Labor/GVP (work hrs/€) | 0.10 | 0.06 | 0.04 | 0.04 | 0.03 |
| GVP (€/yr) | 1.53E+09 | 1.72E+09 | 2.46E+09 | 2.22E+09 | 2.29E+09 |
| **% Contribution to change of total U** | **1985** | **1985-1990** | **1985-1995** | **1985-2000** | **1985-2005** |
| U/F | 0.00 | -6.33 | -0.81 | 1.02 | 20.27 |
| F/(R+N) | 0.00 | 24.00 | 35.17 | 41.31 | -24.78 |
| (R+N)/AA | 0.00 | -5.46 | 4.40 | 1.14 | 32.78 |
| AA/POP | 0.00 | -25.58 | -46.36 | -50.85 | -42.31 |
| POP/Labor | 0.00 | 28.74 | 55.38 | 69.95 | 90.45 |
| Labor/GVP | 0.00 | -38.22 | -108.87 | -110.90 | -137.08 |
| GVP | 0.00 | 11.57 | 56.53 | 45.67 | 51.78 |

*Discussion*

It is very important, for an effective discussion, to remind the theoretical basis of the emergy method. Emergy is not just energy. While the latter indicates the heat content of a source and its ability to raise 1°C the temperature of water, emergy indicates the quality of a resource in terms of time and environmental work invested by biosphere to make it, within a systems thermodynamic framework and Lotka-Odum's Maximum Power Principle (Lotka 1922a,b; von Berthalanfy, 1968; Odum, 1983). As a consequence, emergy accounts for both energy and material sources as well as for the time embodied in their generation, concentration, provision. Consistently with the emergy definition, the renewable emergy R does not only include the renewable energy flows that are actually captured by means of energy devices (photovoltaic, wind turbines, etc), but also include all the typologies of renewable support to the regional agriculture (rainfall, wind, insolation on cropped land), no matter they are converted into electricity through technology or into crops, through photosynthesis. If more renewables are converted to electricity, or agricultural residues are converted to process heat or biofuel, the renewable fraction R does not increase in absolute terms, but may contribute to replace fossil power demand. This is likely to decrease the total emergy use (U), in so affecting the entire set of percentages. Material and energy efficiency and recycling patterns also contribute to decrease the total demand U, thus improving the system's performance and its calculated indicators. This is why the two regional agricultures are affected by both the mix of renewable and nonrenewable resources as well as by improvements in intensity indicators over time.

*Evaluation and trends of emergy indicators*

The fraction of total emergy use that is renewable (Tables 1.14 and 1.15) is an important aspect of sustainable agriculture. In principle, agriculture is an activity based on photosynthesis, that is solar energy driven. When the maximization of the yield is achieved by means of exceeding amounts of non-renewable resources, sustainability is no longer guaranteed. Unfortunately, the use of renewable emergy in both regional agricultures is very small (around 10-12% with L&S and 20-25% without L&S in the two regions, although slightly increasing over time) and requires urgent policy actions to improve this trend. It is important to note that the %REN is more or less the same in the two regions when L&S are accounted for, while it is higher for Campania than Emilia Romagna without L&S. This indicates that more renewable raw sources are used in Campania and that renewability levels off when the resource-intensive societal dynamics comes into play through the emergy cost of L&S, so that the agricultural sector as a whole is characterized by the same low renewability as the entire economy (Pereira et al., 2012). Since the emergy associated to L&S depends on the conversion of money flows into emergy units by means of the national Emergy/GDP ratio, L&S reflect the intensity of emergy use in the Italian economy, in support of welfare and and infrastructures: the same amount of labor (hours applied) would be supported by less emergy in a developing country than in a highly industrialized economy. It is crucial to be able to separate the basic emergy investments as raw matter and energy flows from the societal emergy investment in support to welfare and lifestyle. The emergy costs linked to direct labor and services call for the performance of the entire society: if supporting the welfare of agricultural workers as well as the other workers involved in the upstream supply chain is so resource intensive as to account for about 50% of total emergy costs of agricultural products, this means that it is impossible to improve the performance of the agricultural sector disregarding the need to improve, at the same time, the performance of the economy (better use of resources in the Italian society, in order to support the same or even higher wellbeing with less inputs). Some analysts call for degrowth patterns, others simply call for increased efficiency or expect future technological improvements and cheaper resources to be discovered. The biophysical perspective of the economy from the emergy point of view was explored by Brown and Ulgiati (2011) and cannot be dealt with further in this paper. However, the existence of a strict relation between emergy and economic flows in sectorial, regional and national performances helps understand which fraction of a process performance relies on technical aspects and which fraction instead relies on the socio-economic dynamics of societies.

A land-based intensity of resource use is provided by the empower density indicator (i.e. the intensity of the resource investment per hectare per year) (Figure 1.16). Considering the decrease of land cropped (Figure 1.13), the empower density increased constantly up to values of the same order of magnitude in both regions. This trend may have been affected by several reasons (different mix of crops and input resources, decreased efficiency, increased cost of services for imports). Analytical tables such as Table 1.12 and 1.13 for all years as well as performance tables such as Table 1.14 and 1.15, as well as decomposition techniques help understand how these factors interact and if they are the right basis for a sustainable agriculture.

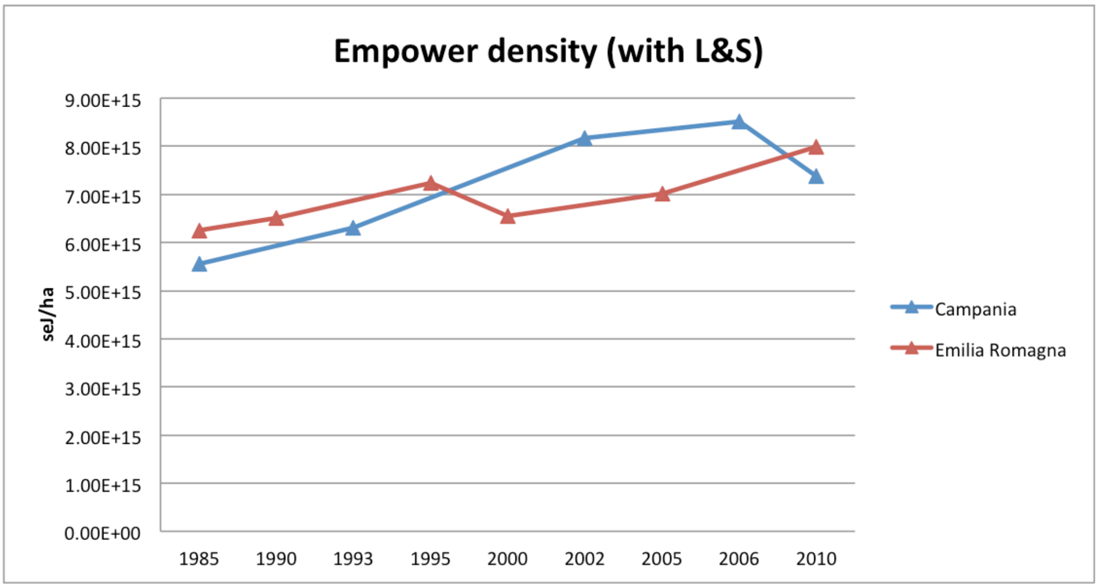

**Figure 1.16.** Trend of empower density in Emilia Romagna and Campania.

The trends of Emergy Yield Ratio (EYR), Environmental Loading Ratio (ELR) and Emergy Sustainability Index (ESI) are also presented in Tables 1.14 and 1.15 and provide new insight into the assessment. The low and relatively constant values of EYR with/without L&S for both agricultural systems indicate that the largest fraction of emergy used to generate the yield is invested from outside the system to drive the process. Unlike past agricultural systems, very self-reliant although at low yields per hectare, modern agriculture increasingly requires huge investments from the main economy in the form of electricity, fertilizers, fuels, etc, while local resources (ground water, soil nutrients and direct insolation) are marginalized. There are signs of slow improvement, likely due to regional and European policies: the ELR shows slightly decreasing patterns (in Emilia Romagna since 1995, in Campania more recently) and so does the %REN indicator. As a consequence of stable EYR and decreasing ELR, the Emergy Sustainability Index (ESI) shows an improvement in both regions in recent times, although still at very low values (Figure 1.17), constantly in the low range 0.10-0.20 for both regions. If the emergy of L&S is not included, it is around 0.20-0.30 for

Emilia Romagna and a higher 0.30-0.50 for Campania, indicating the extent L&S affects agricultural sustainability in both regions.

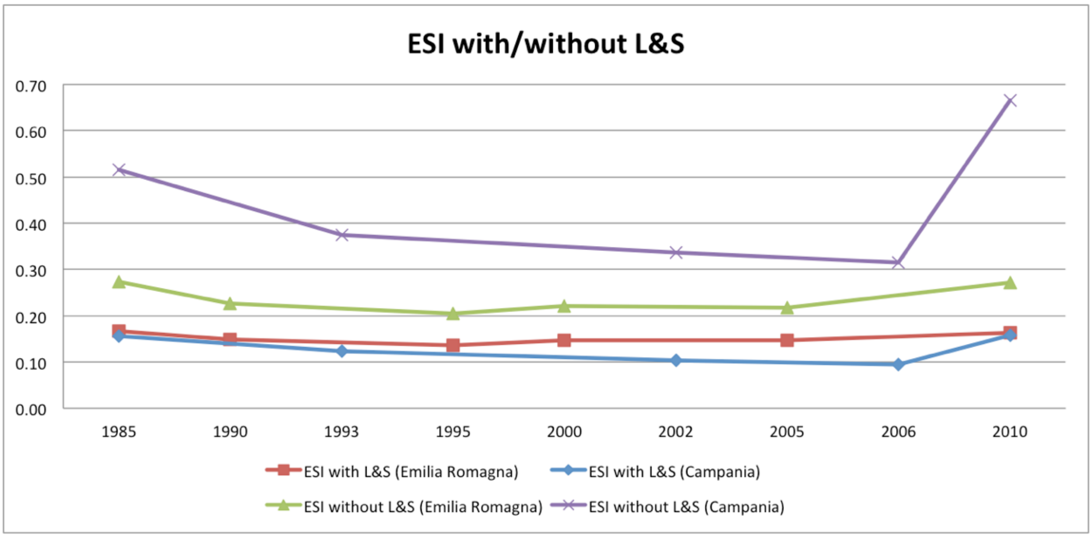


**Figure 1.17.** Trends of the Emergy Sustainability Index (ESI) in both regions, with and without L&S.

*Decomposition analysis*

The main factors capable to drive changes of total emergy use U for the two investigated regions were identified by means of Eqn. (7). Their quantitative assessment is shown in Tables 1.16 and 1.17. Eqn. (7) clearly suggests total emergy U to be linearly dependent on GPV trend, all other factors remaining the same. Instead, changes in the other driving factors introduce non-linearity aspects that need to be carefully taken into account. In order to better discuss their meaning and the extent they affect the investigated regional agricultures, it is useful to compare the performance of the two systems over time in a pictorial way. The contribution of each factor with reference to the year 1985 is diagrammed in Figures 1.18a and 1.18b, although a full understanding of these figures requires a careful look at Tables 1.16 and 1.17 respectively. Our goal is not to ascertain what is good or not, because in complex systems there are interlinkages and feedback effects that affect both desired and undesired results. We try instead to identify the links between each driving factor and the total value U of emergy use by the system in a given year. When the links are clearly identified, suitable policies can be designed based on increased awareness of interdependence of factors.

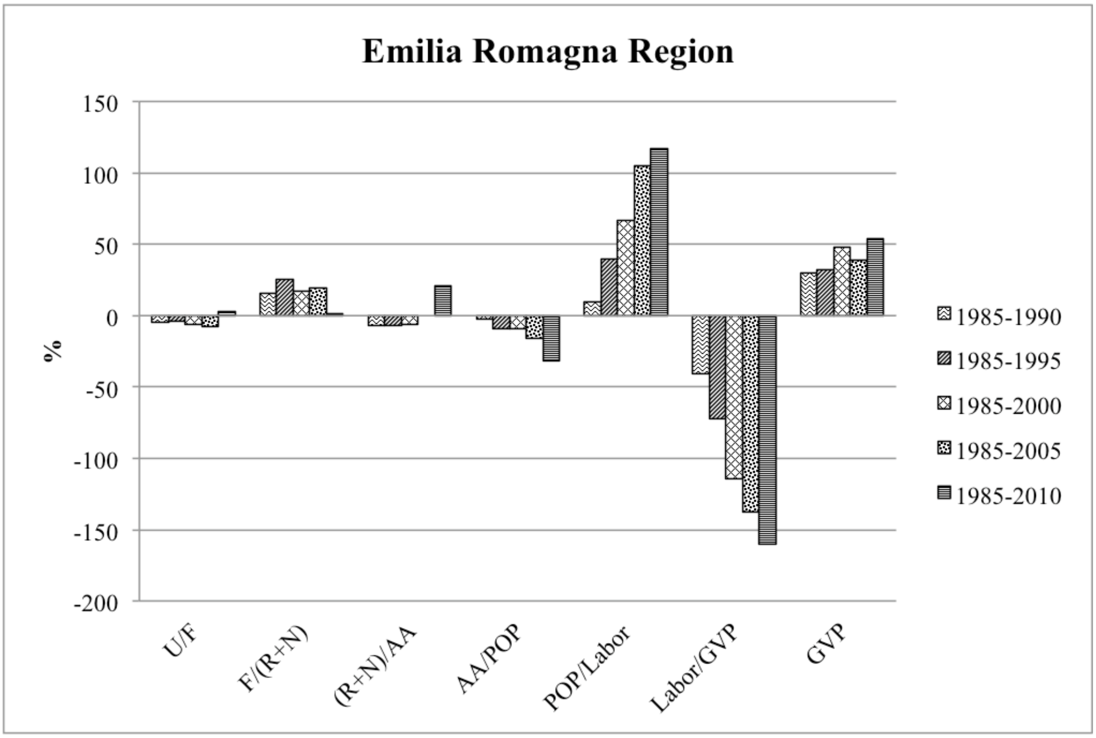


**Figure 1.18a.** Results of decomposition analysis of total emergy U in Emilia Romagna agricultural system.

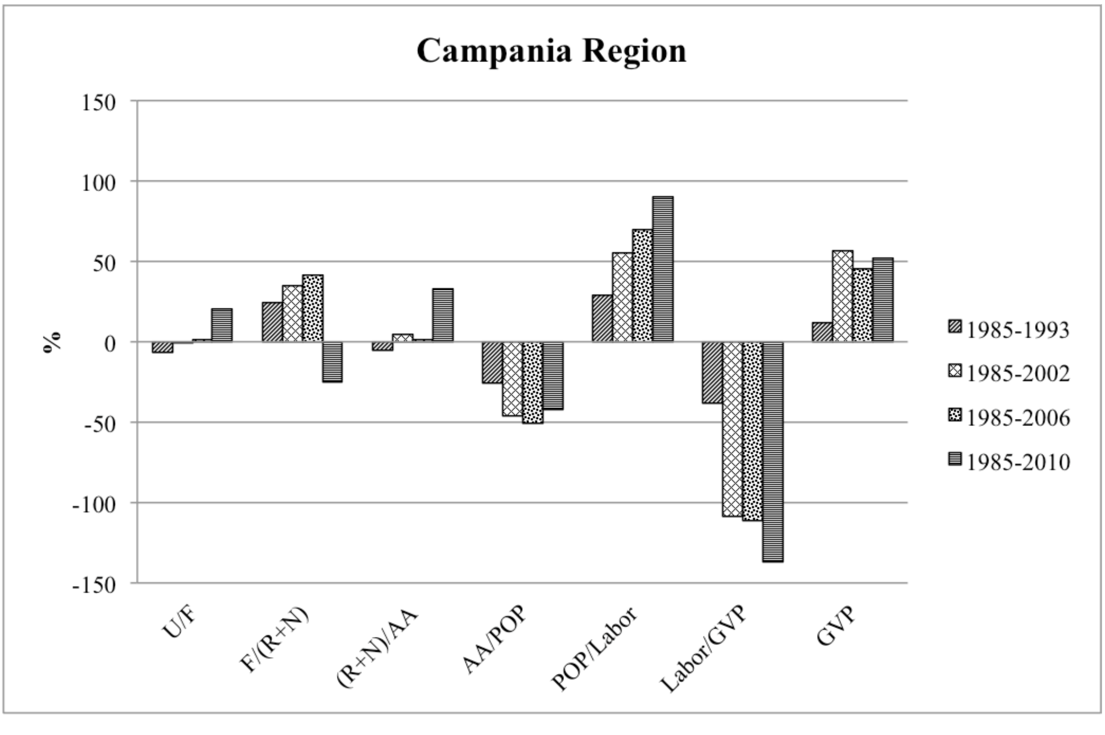


**Figure 1.18b**. Results of decomposition analysis of total emergy U in Campania agricultural system.

The first non-linearity factor is U/F, also named EYR (see Section 2.3), expressing the ability of the process to rely on local resources, no matter renewable or not. The U/F factor slightly decreases, except in the last few years, in Emilia Romagna, while instead it oscillates and finally increases in Campania. For the sake of clarity, a change of U/F may derive from:

(i) numerator: a use change of local nonrenewable resources N (such as ground-water, topsoil organic matter, forest stocks), renewable flows R (such as rain), imported goods F, labor L, services S;
(ii) denominator: a use change of imported resources F (being F both in the numerator and denominator, the impact is a combined effect).

Being U and F relatively stable in the investigated period, the U/F ratio is also relatively stable, and does not contributes significantly to variations of total emergy U. The small changes that are calculated are mainly land-based changes (declining cropped land, declining demand for irrigation, less soil erosion due to soil management policies, more rainfall in most recent years), coupled to oscillations of F.

A similar discussion can be carried out for the second driving factor, EIR= F/(R+N), indicating the efficiency of an external investment in exploiting a unit of local resource. Not all investments are effective in the same way at exploiting local resources, in spite of being, perhaps, economically more profitable. Both regions show that, except in most recent years, a constant and higher outside resource investment was needed over time in order to exploit a unit of local resource in Emilia Romagna, while lower but increasing investments were needed in Campania region. In both cases, investments F contribute to a large extent to increased emergy use, except for Emilia Romagna recently.

Increased rainfall seems to be responsible of increased local carrying capacity (N+R)/AA in recent years; this factor, however, was not an important driver of changes in total emergy use.

The total cropped land (AA) decrease coupled to regional population (POP) increase determines a decreasing per-capita land availability, paralleled by a negative percentage contribution to agricultural emergy use U, likely due to decreased reliance on local agricultural production (more food is imported).

The population that must be fed per hour of invested agricultural work (POP/Labor) is a powerful driver of increased emergy use, likely due to the need for increased productivity per hour of labor.

Finally, labor productivity (Labor/GPV) in terms of ability to generate more GPV on less hours applied contributes significantly to decrease the emergy demand in each investigated year.

A suitable policy would therefore be one capable to support the same amount of product or jobs based on the same (or less) emergy U, with increasing share of local emergy compared to imports, and increased labor productivity. In particular, innovative policies should be implemented on two main factors identified in the present study:

- First, the need to increase the renewable share of emergy use. If more renewable electricity, heat, biomaterials, biofuels, fertilizers are used, this would entail a decreased amount of imported (F) and nonrenewable (N) emergy. If more accurate and efficient water use is implemented, less aqueduct water or ground water will be required, thus improving the performance indicators in both regions and Italy as well.

- Second, the need to become aware of the strict links between cropped land, labor, imports and appropriate marketing, also recognizing how the outside society affects the performance of the agricultural system; a better balance must be achieved among these driving factors in so increasing the overall sustainability of the agricultural sector.

What comes out, however, of the decomposition exercise is that all drivers are linked together, and act as increasing factors in some of the ratios and decreasing factors in others (e.g., Labor), so that the final result in the investigated case is that emergy use remains relatively constant in spite of the huge increase of GPV.

*Conclusions*

An assessment of the agricultural system of Emilia Romagna and Campania regions, taken as representative cases of Northern and Southern Italian agricultural patterns (and ultimately as representatives of the national agriculture of Italy, was performed by combining emergy and decomposition analysis techniques, in order to investigate their sustainability as well as identify the factors which most affected the assessed changes in the period covered by our study. The investigated regional agricultural systems (crop production) are highly dependent on non-renewable emergy flows (N) and purchased input (F) emergy flows. The high values of Environmental Loading Ratios point out this dependence, although slightly decreasing recenty. As a consequence, the Index of Sustainability (ESI) ranks around low values in the range 0.10-0.50.

Decreasing trends of purchased input flows (F) in Campania and non-renewable uses (N) in Emilia Romagna between the years of 1985 and 2010 were identified. However, the total emergy use U in both regions remained more or less constant over the investigated time period, in spite of less cropped land. This is why the empower density was found to increase up to values around 8.0E+15 seJ/ha in both regions. The relative constancy of total emergy use U is the combination of factors driving emergy use variations depending on a multiplicity of interlinked flows and parameters. Land use change, labor productivity, the fraction of population to be fed per hour of agricultural labor and finally the Gross Production Value were identified as the main drivers of total emergy use, compensating each other over time.

The two regions show similar trends of interlinkages among drivers of total emergy use U, in spite of their climatic differences, land cropped, intensity of production effort. Of course, there are important differences in specific factors: for example, the contribution of labor productivity to decreasing emergy use is higher in Emilia Romagna than Campania; the contribution of per capita land availability in decreasing total emergy use is higher in Campania than Emilia Romagna, and so on. However, drivers compensate each other. Such results were not unexpected, since both regions have a good tradition in food production (farmers' expertise, quality, trade) and therefore developed a similar structure of production processes and a similar reliance on imported production factors. It may be inferred that such similar behavior is a consequence of both European and national agricultural policies, similar national regulations, similar national development incentives.

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## *Chapter 1.b Chemicals from biomass: technological versus environmental feasibility towards appropriate material and energy resource use.*

### 1. Introduction

Despite its essential role in our everyday life, chemical industry is commonly charged with its reliance on fossil resources and its production processes that often affect human health and surrounding environment by producing products, by-products and waste, not readily recyclable or degradable after their useful life and sometimes even toxic. Driven especially by concerns over human health and climate change and by the rapid depletion of non-renewable fossil fuel sources, a growing pressure to make chemical production more sustainable and "green" is widespread, thus calling for an integration between social, safety, health, environmental benefits and technological and economic issues.[1,2] Real or claimed damages by conventional chemical routes are also likely to hide the huge benefits that they have also provided in numerous sectors of modern life. It is therefore urgent to identify processes that are capable to keep (or increase) the benefits and minimize the loads.

The use of renewable feedstocks is one of the guiding principles of "green chemistry", introduced in the early 1990s by the US Environmental Protection Agency (http://www.epa.gov/), in order 'to promote chemical technologies that reduce or eliminate the use or generation of hazardous substances in the design, manufacture and use of chemical products', and currently associated with the 12 principles formulated by Anastas and Warner,[3] which advocate a decrease in the environmental impact of a chemical product by considering aspects of its entire life cycle – from raw material to product use and fate.

Biomass represents an abundant carbon-neutral renewable resource with the potential to replace fossil feedstocks as carbon source. Production chains relying on biomass are considered 'short-cycle carbon systems', more sustainable than 'long-cycle carbon systems' based on fossil resources.[4] Enhanced use of biomass would address several challenges, leading to a new manufacturing paradigm for sustainably providing valuable chemicals, in addition to liquid fuels. The advantages of using biomass rather than petroleum to manufacture chemicals and fuels are believed to include opportunities for less pollution, no net $CO_2$ contribution to the atmosphere and more biodegradable and sustainable products. However, the transition from a petroleum-based chemistry to one that exploits the potential of biomass requires the development of innovative, new strategies and technologies, including prevention of land use competition with food production.[5-7] At the moment, bioenergy provides 10% of global primary energy supply, with biofuels, such as bioethanol and biodiesel, expected to grow as transportation fuels from 2% of market share today up to 27% in 2050 (http://www.iea.org). Similarly, chemical products from bio-based raw materials represent only a minor fraction of the output of the chemical industry, mainly due to still higher costs and production processes, needing to be optimized. It is estimated that the share of bio-based chemicals will grow globally (from the 3-4% in 2010) and that in 2050 at least 30% by weight of chemicals will be derived from renewable biomass, thus replacing a considerable amount of fossil resources (http://www.suschem.org).[8] In favorable market conditions, the production of bulk chemicals from renewable resources is expected to reach 113 million tonnes by 2050, corresponding to 38% of all organic chemical production.[9] In particular, the most significant growth is expected from biocommodities, projected to reach 8% already in 2025.[10] Most chemicals that are presently produced from petrochemical resources can be replaced by identical compounds from biomass (e.g. bio-based polyethylene from bio-ethanol) or by biomaterials with comparable properties (e.g. bio-based polylactic acid, PLA, instead of fossil-based polyethylene terephthalate, PET): in the case of such direct substitutions, a bio-based product has to compete on a cost basis against a fossil product which has been optimized over a long time. Cost competition with petrochemicals is instead strategically overcome if a new or improved functionality or characteristic is provided. This is the case of the synthesis of new products such as high-performance biopolymers, obtained by chemical modification of starch or cellulose, with unique properties that the fossil counterpart does not have, towards the establishment of biocompounds in the chemical markets, also characterized by “bio” or “natural” labels, very attractive for marketing purposes.[11] Undeniably, the production volume of bio-based chemicals, mainly consisting of functionalized high-value but low-volume chemicals (pharmaceuticals, cosmetics, biopolymers), is and will be smaller than biofuels, also because of the lack of governmental incentives. Nevertheless, the share of bio-based chemicals is expected to steadily grow for the foreseen development of advanced technologies aimed at highly efficient and cost effective production patterns for bio-based chemicals.[12]

Large efforts are invested worldwide to make the bio-based chemistry technically and economically feasible. On the other hand, the environmental opportuneness of producing chemicals from biomass, in terms of lower impacts over the entire production chain, needs to be carefully assessed as well. The aim of this study is to summarize the current research referring to the most promising biomass value chains and most sustainable technologies and to point out their related environmental impacts. While environmental impacts have been deeply investigated for several bioenergy conversion routes by means of sustainability assessment tools, this is not the case for the majority of platform chemicals (for example, lactic and levulinic acids, furfural, etc), although they are rapidly developing as potential alternatives to fossil-based chemistry. By combining technical feasibility with environmental benefits, a roadmap of possibilities can be identified, in order to determine if the market implementation of bio-based chemicals is not only technically but also environmentally viable in the framework of a more sustainable economy.

## 2. RESEARCH METHOD AND STRUCTURE OF THE REVIEW

This review was designed to identify and critically summarize the recent progresses in the production of chemicals from biomass. The method used is schematized in Figure 1. Scientific literature, published in the last 15-year timeframe, was screened using databases available from major publishers, such as, but not only, Scopus, Google Scholar and Sciencedirect. Since the scope of this review is to evaluate the production of chemicals from biomass, studies only focusing on biofuels were excluded. A first step was the selection of peer-reviewed papers dealing with (1) typology of biomass feedstock as a source of chemicals, (2) conversion pathways and (3) products that can be potentially obtained, with a special attention to platform chemicals as key intermediates between raw materials and final products. The state-of-the-art emerging from selected papers was referred to as the starting point to draw a general overview of the technical feasibility (Section 3), in terms of identifying the available biomass to be suitably processed for the production of chemicals (Section 3.1), the most recent trends in bioconversion routes (Section 3.2) as well as the target molecules that can be isolated from biomass and further converted to value-added products (Section 3.3). Moreover, the economic feasibility of bio-based chemicals production is closely linked to the technical feasibility and is presented in Section 3.4. A further step was the review of studies referred to the environmental sustainability assessment of production processes of bio-based chemicals, in particular by means of Life Cycle Assessment (LCA), and the main findings are reported in Section 4. Finally, Final conclusions and recommendations are provided in Section 5.

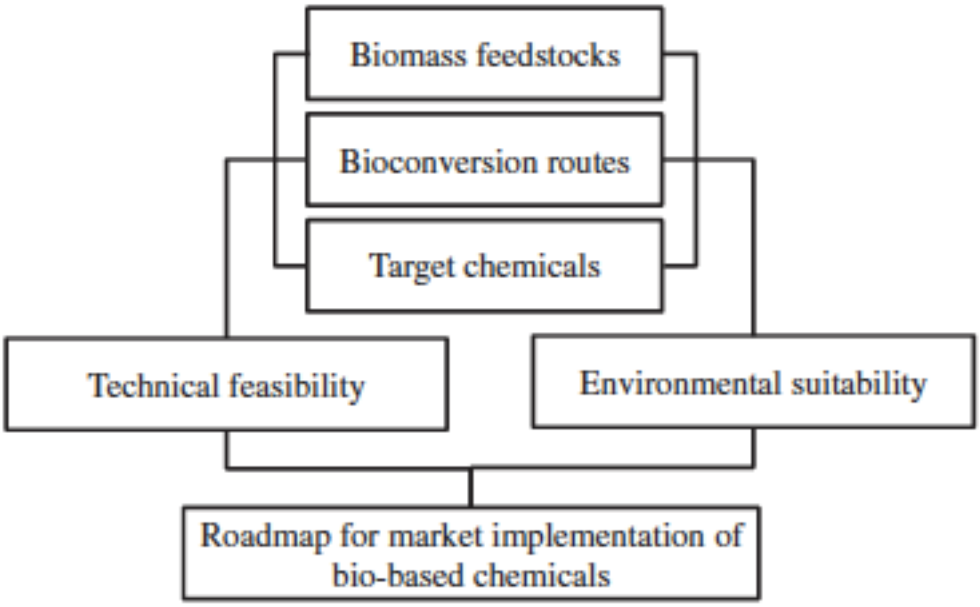



Figure 1. A schematic fl owchart of the research steps followed in this study.

## 3. TECHNICAL FEASIBILITY

According to the scientific literature survey carried out, the most common scheme of production of chemicals from biomass is the conversion of carbohydrate biopolymers, by means of depolymerization and/or fermentation steps, into platform molecules. These are then employed as building blocks for the synthesis of intermediates and fine chemicals, via heterogeneous and/or homogenous catalytic processes. Biomass conversion process thus involves different steps: the choice of a suitable biomass, an effective pretreatment and conversion pathway and, finally, the downstream processing to the target chemical through derivatives of platform chemicals. The process flow of bio-based chemicals is schematically drawn in Figure 2.

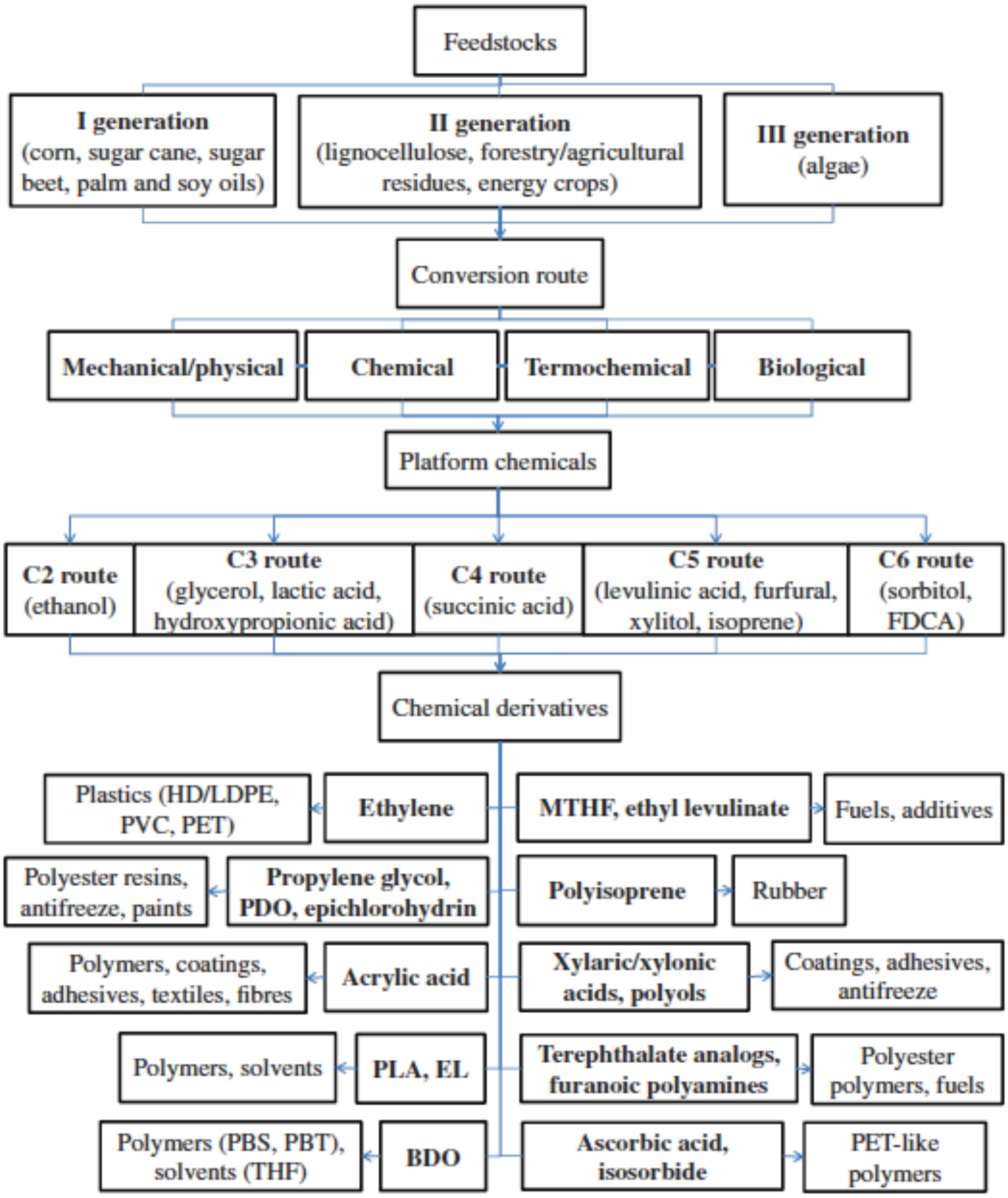



**FIGURE 2.** Figure 2. Schematic process fl ow of bio-based chemicals (FDCA: 2,5 – furandicarboxylic acid; HDPE: high density polyethylene; LDPE: low density polyethylene; PVC: polyvinylchloride; PET: polyethylene terephthalate; PDO: 1,3 – propandiol; PLA: polylactic acid; EL: ethyl lactate; BDO: 1,4 – butanediol (BDO); PBT: polybutylene terephthalate; PBS: polybutylene succinate; THF: tetrahydrofuran; MTHF: methyltetrahydrofuran).

## 3.1 Biomass as a source of chemicals

The first challenge in the implementation of a bio-based chemistry is the identification of suitable biomass to be used as an alternative to fossil feedstocks. From a chemical point of view, biomass has a very heterogeneous nature: it is mostly composed of a mixture of single components such as cellulose, hemicellulose, starch, chitin and lignin. In addition, depending on the source, biomass can also contain proteins, fats, waxes, organic acids, minerals and free sugars as their structural or metabolic components. The characteristics of the main constituents of biomass have been extensively investigated, concerning both the morphological distribution and the chemical structure, in order to facilitate their use as potential sources for energy and chemical products extraction through appropriate conversion methods.[13]

Gallezot[11] highlighted that the chemical structure of renewable raw materials should be the first selection factor for the synthesis of a targeted chemical. For example, flavors and fragrances should be derived from terpenes, fatty compounds and lignin could be suitable for the production of oleochemicals and phenolic compounds, respectively, while carbohydrates offer a much larger field of applications.[14] In particular, carbohydrates such as starch and cellulose are generally the most widespread organic feedstock for producing commodity and specialty chemicals: many bulk chemicals and polymers can be produced by chemical modification or fermentation of starch and its monosaccharide derivative (D-glucose).[15] Currently, bio-based commodity chemicals, such as lactic acid and 1,3-propanediol, are being produced from sugaror starch-rich crops, generally referred to as 'first generation feedstock'. However, it is widely acknowledged that the next generation of bio-based platform chemicals will mainly exploit 'second generation feedstocks', consisting of non-food sources, such as inedible oilseed crops and perennial grasses, and lignocellulosic biomass, i.e. the residual non-food parts of current crops, including agricultural and forestry waste, such as straw, bagasse, molasses and harvesting residues, as well as fast-growing energy crops, not to compete with food demand by a hungry planet.[16, 17]

Conversion of lignocellulosic biomass, in particular, is very promising, due to abundant availability at low price.[18,19] Lignocellulose, being the major non-food component of biomass, proves an almost unlimited source of $C_5$ and $C_6$ sugars without interfering with food demand. As shown in Figure 3, lignocellulose is a complex carbohydrate polymer mix composed of three main fractions, namely cellulose (around 30-50% by weight), hemicellulose (20–40% by weight) and lignin (15–25% by weight). Cellulose is a long-chain homopolymer of D-glucose units linked by β-1,4-glycosidic bonds. It is linear and contains amorphous and crystalline portions, with extensive intramolecular and intermolecular hydrogen bonding networks, which can lead to the separation of important building blocks (e.g. levulinic acid, 5-hydroxymethylfurfural) upon pretreatment via hydrolysis followed by dehydration. Hemicellulose is a highly branched heteropolymer of pentoses (β-D-xylose and α-L-arabinose), hexoses (β-D-glucose, α-D-galactose and β-D-mannose) and sugar acids (α-D-glucuronic, α-D-galacturonic and α-D-4-O-methylgalaturonic acids) with small amounts of other sugars, such as α-L-rhamnose and α-L-fucose.[20] Its average degree of polymerization is much lower than cellulose and the breakdown of components with chemicals or heat results easier. Lignin, the most complex and recalcitrant fraction, is an amorphous and highly irregular aromatic polymer, consisting of phenylpropane units, namely syringyl (S), guaiacyl (G) and p-hydroxyphenyl (H) units. Lignin fills in the network of fibers where cellulose and hemicellulose are interweaved, building up a rigid structure for the plant cell wall and making cellulose and hemicellulose inaccessible, unless a specific chemical or physical pretreatment is implemented to depolymerize the lignin and extract cellulose and hemicellulose. Unlike cellulose and hemicellulose, lignin cannot be hydrolyzed to sugars and then fermented to ethanol, which makes lignin a suitable candidate feedstock for many other purposes (chemical extraction or energy generation).

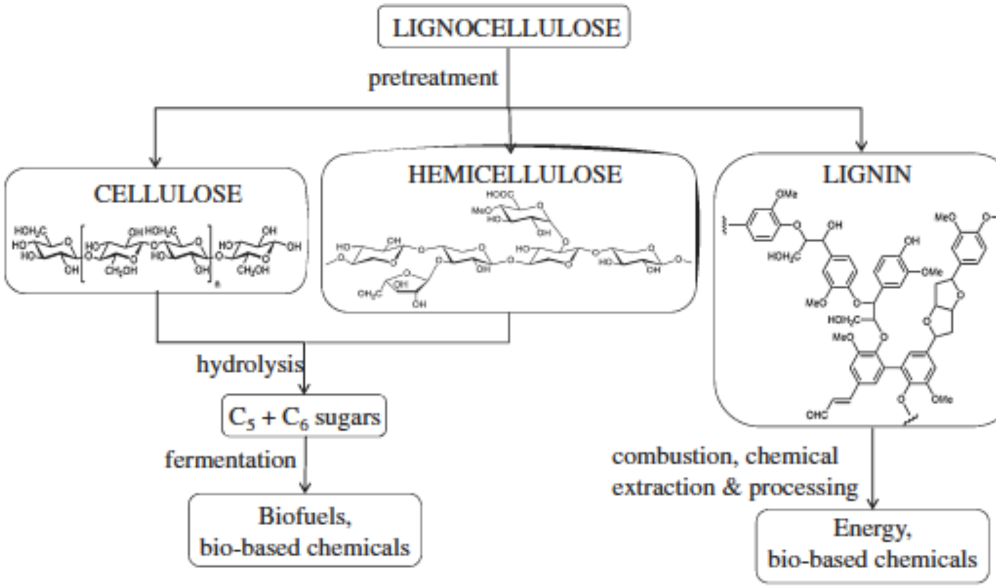



Figure 3. Chemical structure of lignocellulosic components and potential treatments and products.

Another renewable resource is represented by oil seed plants (especially soybean, rapeseed, sunflower and oil palm, whose oil compositions are shown in Figure 4): their exploitation for the production of fatty acids, glycerol and other triglycerides is less conspicuous than that of carbohydrates, because of a severe competition not only between food needs and industrial applications, but also between biodiesel and oleochemical production (surfactants, lubricants, plasticizers, polymers).[21] Nowadays, vegetable oils are mainly used for the production of biodiesel via a reaction with an alcohol, usually methanol. In addition, they can be used as a substrate for chemical reactions thanks to two chemically reactive sites: the double bond in the unsaturated fatty acid chain and the acid group of the fatty acid chain (Figure 4).[22] However, oilseed crops are characterized by low yield and high use of production inputs. Conversely, algae represent a likely source of triglycerides and progresses in algae production and processing may translate in an increased production of biodiesel and bio-based oleochemicals. Like carbohydrate and oilseed crops, algal feedstocks are capable to provide biofuels and bio-based chemicals, while simultaneously reducing emissions of $CO_2$ and global warming and are included in the so-called "third generation feedstock":[23,24] due to their high lipid content, by means of hydrothermal liquefaction algae can produce bio-oils with an energy content comparable to fossil reference values.[25] Moreover, the fast recycle and high production rates of algae compared to crops, grasses and forest resources, together with a much minor land area requirement for lipids production, i.e. 5-14 $km^2$ *versus* 35 $km^2$ required for equivalent amounts of palm oil production,[4] support the recent trend in the scientific literature to switch to this resource.[26-28] Nevertheless, in order to make algae a competitive feedstock for bio-products, appropriate conversion technologies still have to be developed and a substantial cost reduction still needs to be achieved.

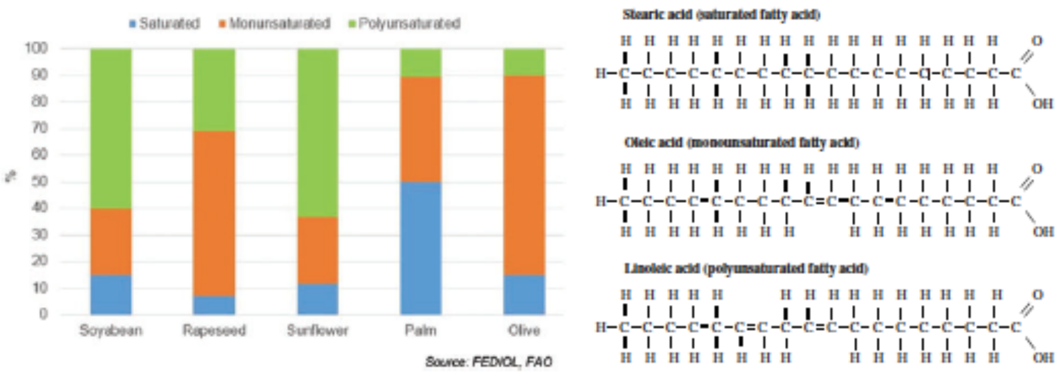



Figure 4. Fatty acid composition of vegetable oils (Source: FEDIOL, FAO) and chemical structure of the most common saturated, monoand poly-unsaturated fatty acids.

Whatever biomass feedstock is selected, there is large consensus about the fact that the most efficient approach for the sustainable valorization of biomass resources in a future bio-based economy is the production of both bio-based products and energy carriers in integrated biorefineries, namely "the sustainable processing of biomass into a spectrum of value-added products (chemicals, materials, food and feed) and energy (biofuels, power and heat)", thus linking the production of chemicals to the rapidly emerging bio-energy industries.[29-31] A variety of biomass sources has been tested for biorefinery applications, such as cultivated crops, agricultural waste, forest resources, urban and industrial waste and algae, resulting into a multiplicity of identified solutions.[32,4] The application of biorefinery technologies offers the main advantage of providing a sufficient supply of biomass to accommodate the additional demand from the chemical industry, by enabling an efficient use of biomass components rather than increasing the field production of crops: full use of biomass, together with minimization of transportation costs, in fact, are basic requirements for effective biomass utilization processes. Furthermore, how much biomass has to be produced for implementing a bio-based industry is a crucial issue: the demand of chemical industry for resources is globally minor than for energy, but, in order to offer a solution that can be sustainable on the long-term, the production of targeted bio-products should be commensurate with the availability and cost of raw resources, without generating environmental and social impacts, related to overall land availability and use as well as to competition with food production. Different attempts to quantify the biomass needed have been made: Sanders et al.[8] estimated the production volume of chemical industry worldwide between 1400 and 1750 Mt/a, 300 Mt/a of which could be substituted by bio-based chemicals, with a consequent demand for biomass of 280 Mt in Europe (for the production of 65 Mt/a of chemicals). In addition, Bos and Sanders[33] considered the substitution of 20% of fossil fuels by biofuels and the production of 10% of the EU electricity from biomass, totaling an annual biomass requirement of 700 Mt in Europe: in the Authors' opinion, such a demand to produce required biofuels and platform chemicals in the petrochemical industry in Europe can be covered without significant changes to the current agricultural land use.[34] Congruent conclusions were achieved by Kajaste[4], according to which, and to references therein, lignocellulosic matter resulting from photosynthesis and natural oil and fat stocks can be conservatively estimated to amount respectively to 1.3E9 and 132E6 tons per year, thus overcoming the world sugar production (150E6 tons in the 2008/09 season). If forest resources as well as algae and microalgae produced in industrial fermentation units are summed up, the long-term availability of biomass sources seems to be guaranteed.[4]

## 3.2 Conversion routes

Identifying the best pathway to convert biomass to a given chemical can be challenging because there is a plethora of potential targets that can be obtained by means of different reactions, starting from different substrates. Figure 5 shows a schematization of processing routes that lignocellulosic biomass can undergo. In order to optimize the bioconversion route, it is crucial to have a deep understanding of and potential access to all the available technology options including mechanical/physical, chemical, thermochemical and biological processes, or a combination of them.

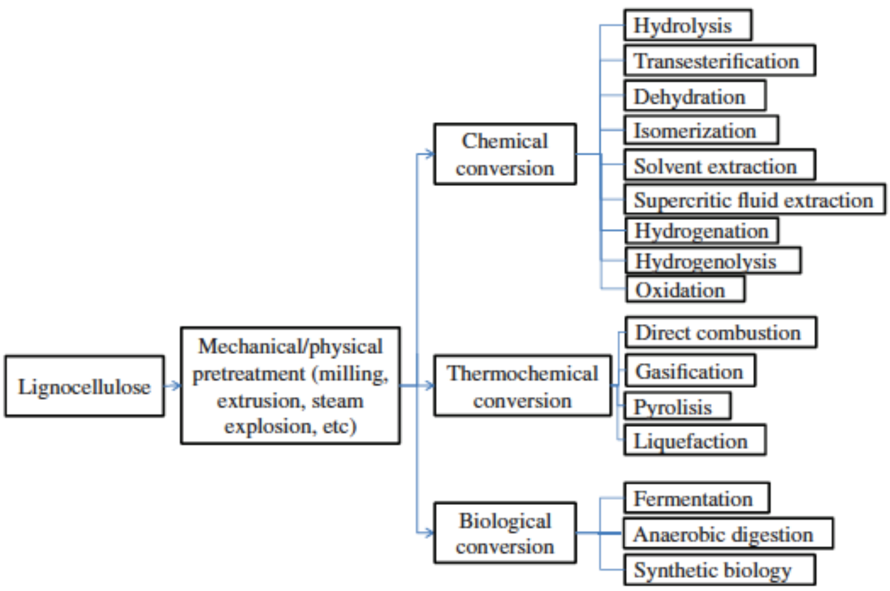


Figure 5. Processing routes of lignocellulosic biomass.

*3.2.1 Mechanical/physical routes*

Mechanical/physical processes, such as milling, irradiation by gamma rays, electron beam or microwaves, extrusion and steam explosion, are most often used to perform a size reduction or a separation of the substrate into its main components, without changing its state or composition.[35] The mechanical extraction of crude oil from oil seeds by means of a screw press to recover and concentrate triglycerides from a bulk and inhomogeneous substrate is the most common method to produce biodiesel nowadays. A chemical conversion of extracted oils then follows.[36,37]

*3.2.2 Chemical routes*

Chemical conversions refer to processes, such as hydrolysis, transesterification, dehydration, isomerization, solvent extraction, supercritical fluid extraction, hydrogenation, hydrogenolysis and oxidation, which directly convert biomass to chemicals, changing the chemical structure of the substrate, at relatively mild temperature and/or pressure and in the presence of a catalyst.[38] Chemical conversions are involved in the pre-treatment of biomass as well as in the downstream processing steps to convert the chemical intermediates, produced from thermochemical or biological conversions, to final chemical products. Hydrolysis, for example, uses acids, alkalis or enzymes to cleave glycosidic bonds and depolymerize polysaccharides and proteins into simpler sugar monomers, e.g. glucose from cellulose, or derivate chemicals, e.g. levulinic acid from glucose.[39] Dehydration of carbohydrate substrates is used for the production of numerous platform furan compounds and liquid alkanes.[40,41] Propylene glycol, 1, 2-propanediol and 1, 3-propanediol are commonly produced by hydrogenolysis of glycerol,[42-44] whereas selective oxidation of glycerol generates formic, lactic and oxalic acids.[45] Demirbas reported promising results in the recovery of bio-based chemicals also by means of supercritical fluid extraction.[46]

The role of catalysts in these conversion pathways is critical and many research efforts are now focusing on the optimization of catalysts' efficiency and on the design of heterogeneous catalysts, applicable in a wide range of reaction conditions and that can be easily recovered from the reaction mixture and reused.[47,48]

*3.2.3 Thermochemical routes*

Thermochemical conversions include direct combustion, gasification, pyrolysis or liquefaction, that mostly involve the processing of biomass at temperature and/or pressure conditions harsher than chemical routes.[49] Direct combustion involves the burning of biomass in an oxygen-rich environment mainly for the production of heat, Whereas gasification consists in treating biomass at high temperature (> 700° C) with low oxygen levels to produce a mixture of $H_2$, CO, $CO_2$ and $CH_4$, the so-called syngas, that can be used directly as a stationary biofuel or as a chemical intermediate for the production of fuels or chemicals, by means of Fisher–Tropsch synthesis.[50] On the other hand, pyrolysis uses intermediate temperatures (300 – 600° C) in the absence of oxygen to convert the biomass feedstock into a mixture of aromatic and aliphatic compounds named liquid pyrolytic oil (or bio-oil), solid charcoal and light gases similar to syngas.[51] Biomass is also converted into a liquid product by means of the thermochemical liquefaction process, that, unlike pyrolysis, requires the presence of a catalyst and operates in wet conditions.[52]

*3.2.4 Biological routes*

Biological conversions, such as anaerobic digestion and fermentation, have been recognized to be among the greenest technologies and involve the utilization of enzymes or living organisms to catalyze the conversion of biomass into chemicals and are often referred to as biocatalytic processes or "white biotechnology".[2,53-55] In the last decades, bioprocesses have found application in the production of high value products such as pharmaceuticals (and their intermediates) and, in more recent years, they have also been applied to bigger volume products such as fine chemicals, bulk chemicals and fuels.[56] The hydrolysis of cellulose to monomeric sugars by cellulolytic enzymes, such as cellulases and hemicellulases, has been investigated intensively since the early 1970s, with the objective of developing a method for the production of ethanol and is now a consolidated process.[57,58] Yeast and bacterial fermentation processes are commonly used to produce ethanol in particular, but also other commercial chemicals, such as lactic acid, citric acid and acetone-butanol.[59-61] Hexoses, mainly glucose, are the most frequent fermentation substrates, while pentoses, glycerol and other hydrocarbons required the development of modified fermentation organisms to enable their conversion to ethanol. Indeed, recent advances in fermentation technologies, such as enzymatic and metabolic engineering or synthetic biology, provide new opportunities for improving bioprocesses and broaden the spectrum of products that can be obtained, by optimizing metabolic pathways through genetic modifications aimed at manipulating metabolic capabilities of microbes. The constant development of synthetic biology tools that both reduce the time required for genetic constructs as well as increase their predictability and reliability greatly improves metabolic engineering techniques for the effective production of a wide variety of fuels and chemicals.[62-65] High yield and selectivity, as well as minimum waste streams, favor biological conversions as pathways to transform biomass to higher-value chemicals. Nevertheless, there are still improvements to be adopted to recover chemical products from fermentation and microbial-based or enzyme-based biocatalysis and to increase efficiency and decrease energy requirements of these technologies.

The outlined survey of bioconversion routes underlines the high level of criticality of the biomass processing and of pretreatment steps in particular: physical, physico-chemical, chemical and biological pretreatments, or their combinations, are crucial to facilitate the solubilization or separation of the major components of biomass, i.e. cellulose, hemicellulose and lignin in the case of lignocellulosic biomass. Once pretreated, biomass can be processed using different process configurations such as separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF), simultaneous saccharification and co-fermentation (SSCF) and consolidated biomass processing (CBP).[35] Sanders and colleagues[8] pointed out the necessity to highly intensify and preferably combine all processing steps to reduce the number of unit operations. Moreover, in order to make the quality and price of chemicals competitive with respect to products obtained via traditional routes from fossil fuels, efficient processes adapted to the molecular structure of highly functionalized biomass molecules have been suggested[11]: (1) flexible catalytic processes are required to cope with variations in feedstock availability and molecular structure, (2) robust and easily regenerated catalysts need to be developed because natural raw materials may contain impurities which could alter their selectivity and decrease their activity, (3) new reaction media, such as supercritical fluids and ionic liquids, and activation systems, like ultrasounds or microwaves, should be employed. Schwartz and colleagues[66] proposed the integration of chemical and biological catalysis, by using the latter as the front-end for biomass upgrading strategies for the selective de-functionalization of sugars to platform molecules that are suitable for conversion to final products by using the former. Their suggested approach would provide the flexibility required for a biomass conversion process to adapt to the evolving needs of chemical industry. In line with the purpose of a more sustainable chemical production, biomass conversion processes should also follow the principles of green chemistry to minimize waste and energy and most of the above mentioned goals can be achieved by integrating green chemistry methodologies and techniques into biorefineries.[67] Green technologies that offer future opportunities to combine renewable feedstocks, sustainable bio-based chemical processing and the production of genuinely green and sustainable products are microwaves and ultrasounds.[68,69] When microwave or ultrasound radiation is used to convert cellulosic biomass into valuable chemicals, including liquid and solid fuels, the challenge is to selectively convert biomass into molecular products, avoiding side reaction pathways in the decomposition process, as well as to keep the energy efficiency of the technique cost-effective and environmentally beneficial. Another model of green technology is the supercritical fluids extraction technology that overcomes concerns over atmospheric damage, greenhouse gas accumulation, and operator health and safety issues, related to the use of solvents in chemical processing. Carbon dioxide into the supercritical state is recognized as a green solvent, since it is non-flammable, non-toxic, available as byproduct of many conversion technologies (e.g. biomass fermentation) and gives no solvent residues, offering a wider range of solvent strengths by using different combinations of temperature and pressure.[70] Furthermore, biomass processing in ionic liquids (ILs) has been extensively tested and is a promising solution for integrating pre-treatment, hydrolysis and conversion of lignocellulose in one pot.[71]

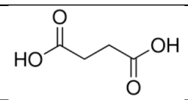
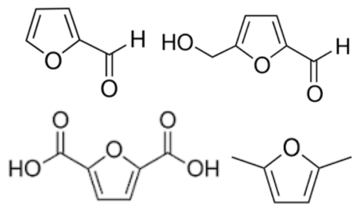
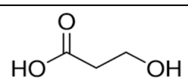
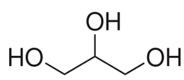
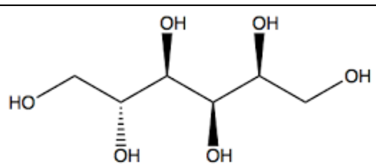
### 3.3 Target molecules

Concerning the vast range of possible target molecules, chemical research is currently focusing on the production of platform chemicals that can be derived from biomass as key intermediates between raw materials and final products and can be converted by means of mixtures of chemical, thermochemical and biological processes into a multitude of high-value added marketable products.

A first selection of 12 platform chemicals, produced either biologically or chemically from renewable carbohydrate raw materials and considered as potential building blocks for the future, was reported by the US Department of Energy in 2004,[72] including 1,4 – dicarboxylic acids (succinic, fumaric and malic acids), 2,5 – furan dicarboxylic acid, 3 – hydroxypropionic acid, glycerol, sorbitol, xylitol/arabinitol, levulinic acid, aspartic acid, glucaric acid, glutamic acid, itaconic acid and 3 – hydroxybutyrolactone. More recently, the selection was updated and further restricted to 10 target molecules, including succinic acid, furanics, hydroxypropionic acid/aldehyde, glycerol and derivatives, sorbitol, xylitol, levulinic acid, biohydrocarbons, lactic acid and ethanol.[73] Such a selection allows an easier focus on a limited number of platform chemicals in order to progress on their production technologies. The selected platform chemicals are, in some cases, end products themselves, but in general are used as building blocks and are further converted to a wide spectrum of derivatives through chemical processes, such as reduction, oxidation, dehydration, hydrogenolysis and direct polymerization, and widely used as solvents, fiber, antifreeze and polymers (such as polyesters, polyamides, and polyurethane) with polymeric properties comparable with those currently derived from petroleum.

The 'Top 10' platform chemicals and their potential uses are roughly described below and their chemical formulas and structures are displayed in Table 1, but more exhaustive and comprehensive details can be found elsewhere.[74-76]

**Table 1.** 'Top 10' platform chemicals and their chemical structure.

| n. | Platform chemical | Chemical formula | Chemical structure |
|---|---|---|---|
| 1 | Succinic acid | $C_4H_6O_4$ |  |
| 2 | Furanics (such as furfural, 5–hydroxymethylfurfural, 2,5–furandicarboxylic acid, 2,5–dimethylfuran) | $C_5H_4O_2$, $C_6H_6O_3$, $C_6H_4O_5$, $C_6H_8O$ |  |
| 3 | Hydroxypropionic acid | $C_3H_6O_3$ |  |
| 4 | Glycerol | $C_3H_8O_3$ |  |
| 5 | Sorbitol | $C_6H_{14}O_6$ |  |

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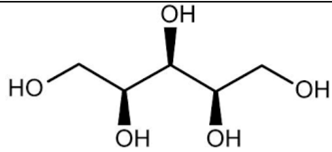
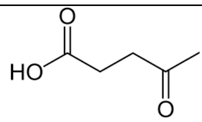
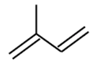
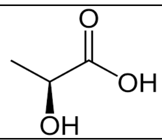
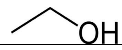
|---|---|---|---|
| 6 | Xylitol | $C_5H_{12}O_5$ |  |
| 7 | Levulinic acid | $C_5H_8O_3$ |  |
| 8 | Biohydrocarbons (such as isoprene) | $C_5H_8$ |  |
| 9 | Lactic acid | $C_3H_6O_3$ |  |
| 10 | Ethanol | $C_2H_6O$ |  |

1. Succinic acid is one of the most attractive platform chemical, due to its widespread applications in fields ranging from chemical solvents to plasticizers and pigments. It is currently produced by catalytic hydrogenation of maleic acid or anhydride, but the bio-based production by means of bacterial fermentation of carbohydrates is steadily increasing, accounting for 3% of the current succinic acid market.77,78 Succinic acid can be converted to 1,4 – butanediol (BDO), an important intermediate in the production of polymers such as polybutylene terephthalate (PBT) and polybutylene succinate (PBS) and of solvents such as tetrahydrofuran (THF).
2. Furanics include $C_5$ containing compounds, like furfural and 5 – hydroxymethylfurfural (HMF), and $C_6$ containing compounds, like 2,5 – furandicarboxylic acid (FDCA) and 2,5 – dimethylfuran (DMF), produced by chemical dehydration of $C_5$ and $C_6$ carbohydrates. Potential derivatives of furanics are levulinic and succinic acids as well as polyethylene, terephthalate analogs and furanoic polyamines that can be polymerized to produce furanoic polyesters and polyamide for nylons.[79,80] Indeed, FCDA has been suggested as a replacement for terephthalic acid in the production of polyester polymers[81], whereas dimethylfuran has been proposed as a potential biofuel.[82]
3. Regarding the hydroxypropionic acid, its main derivative through chemical dehydration is the acrylic acid, an important building block used in the production of polyacrilates and commodity acrylates, the former being super absorbent polymers, the latter used in a variety of industrial applications including coatings, adhesives and sealants, textiles and fibres, polymer additives and films.[83]
4. Glycerol, commonly known as glycerin, can be found in all natural fats and oils as fatty esters and is produced by chemical or enzymatic transesterification of oils. The reactive nature of its molecule allows reactions of esterification, oxidation, hydrogenolysis and polymerization to generate a large variety of derivatives, such as glyceric acid, propylene glycol, 1,3 – propandiol, branched polyesters and polyols, epichlorohydrin, among others.[43,84,85] The industrial applications of

glycerol and its derivatives range from the use of propylene glycol to produce unsaturated polyester resins, coolants and antifreeze, aircraft de-icing fluids, paints and coatings to the production of epoxy resins, paper reinforcement and water purification via epichlorohydrin. Glycerol is not only widely used as building block, but also as a substrate for certain fermentative processes instead of carbohydrates.[86]

5. Sorbitol is produced on large industrial scale by nickel catalyzed hydrogenation of glucose and can be used for producing food, surfactans and polyurethanes.[87] Potential derivatives via hydrogenolysis are ascorbic acid, isosorbide and anhydrosugars for producing PET like polymers, propylene glycol and lactic acid as well as branched water soluble polysaccharides.[88,89]
6. Xylitol is derived by hydrogenation of xylose, the main pentose in hemicellulose, and is presently used as naturally occurring sweetener.[90] It can be oxidized to xylaric and xylonic acids or converted into polyols, such as ethylene and propylene glycol, to be used as antifreeze.
7. Levulinic acid is produced by acid treatment of starch or lignocellulosic substrates: firstly, cellulose is hydrolyzed to $C_6$ sugars and then levulinic acid is obtained through hydration of hydroxymethylfuran (HMF), with an efficiency of 50% and the side production of formic acid. Also $C_5$ carbohydrates from hemicellulose can be converted into furfural and eventually upgraded to levulinic acid by adding a reduction step after the acid treatment, according to the Biofine process.[91] Afterwards, due to the presence of two very reactive groups (a ketone carbonyl group and an acidic carboxyl group), levulinic acid can be converted into a vast number of derivatives, such as methyltetrahydrofuran (MTHF), a biofuel which can be blended with gasoline and is obtained by dehydratation and hydrogentation of levulinic acid, δ-aminolevulinic acid (a herbicide which can be produced after a chemical synthesis process), diphenolic acids (a polymer constituent produced by reaction of levulinic acid with phenols), ethyl levulinate (a transportation biofuel, produced after reaction with ethanol, which can be added to conventional diesel).[92,93]
8. Biohydrocarbons, such as isoprene and farnesene, are molecules that can be obtained by fermentation of carbohydrates thanks to recent advances in synthetic biology.[94] Isoprene, in particular, is used for the production of polyisoprene and butyl rubbers for products like surgical gloves or car tyres.
9. Lactic acid produced from the bacterial fermentation of starch amounts to around 90% of the total worldwide lactic acid production.[95,96] It is commonly used in the food and beverage sectors as a preservative and pH adjusting agent, in the pharmaceutical and chemical industries as solvent and in the cosmetics as a standard or active ingredient. It can be used for the production of various other chemicals (acrylic acid, propylene glycol, acetaldehyde) and its polymerization produces the biodegradable polymer polylactic acid (PLA), which is utilized in food packaging. Another commercialized derivative of lactic acid is the green solvent ethyl lactate (EL), with properties superior to many conventional petroleum-based solvents.

10. Finally, bio-based ethanol production has expanded rapidly due to the global demand for biofuels.[97,98] Bioethanol is an end product but also the basis for the synthesis of many important chemicals, such as ethylene, propylene, 1,3-butadiene, iso-butylene, hydrogen, acetaldehyde, ethylene oxide, n-butanol, acetic acid, ethyl acetate, acetone and dimethyl ether.[99] The production of ethylene through dehydration is particularly relevant, since ethylene is commonly used for yielding high volume plastics, such as polyethylenes (high density polyethylene HDPE, low density polyethylene LDPE and linear low density polyethylene LLDPE), polyvinylchloride (PVC) and polyethylene terephthalate (PET), through co-polymerization of mono-ethyleneglycol (MEG) with terephthalic acid.

### 3.4 Economics of a bio-based chemistry

The technical feasibility of platform chemicals from biomass is not sufficient by itself to shift chemicals' production to renewable sources and cleaner processing pathways. In such a transition, economic drivers play a role as important as technical issues, although economy-related aspects (feasibility, prices) are affected by subjective and very unstable market factors (demand and offer, fossil resource market strategies, geopolitical situation, among others) that make any assessment very uncertain. Nevertheless, the cost effectiveness of biomass as feedstock for chemical production is a crucial parameter to investigate the feasible implementation of a bio-based chemistry that cannot be disregarded. Unlike biofuels, the economic aspects of biomaterials have been scarcely assessed in the existing literature.[100,101] Production costs and sale prices of bio-based compounds were compared to those of their fossil equivalents in the updated BREW model[9] as well as in Hermann et al[102], and an economic profitability was reported for a number of biomaterials (such as bio-ethylene and PLA, among others). Cost competitiveness for ethylene, PLA and PHA from low-cost Brazilian sugar-cane was also reported by Gerssen-Gondelach and colleagues, on the basis of a cost data standardization applied to calculate levelized production costs.[103] Saygin and colleagues[104] compared the economic value of bioand fossil-based chemicals, in terms of their product value, defined as the total sum of production costs and profits. Their results indicated that the current worldwide production costs of bio-based materials are heavily dependent on the feedstock. When bio-based products are derived from low cost sources (such as biomass residues), the cost competitiveness of bio-based *versus* fossil-based is still likely to be addressed and achieved by means of improved bio-technologies and market expansion, beyond the lower performance of early research and production phases. For example, when the process is based on biomass residues, bio-ethylene is approximately 30% more expensive than its fossil counterpart, PLA price is only slightly higher than the average price of all polymers it could theoretically replace and starch polymers price is about 60% higher than LDPE. Conversely, when expensive feedstocks, such as dedicated crops, are employed, the production prices of bio-based materials overcome those of fossil-based ones by a much larger extent, hard to be reduced. Even less favorable conditions were observed by the same authors for materials which currently have smaller capacity or are only in a phase of research development, while cost competitiveness is achieved only for bio-based materials replacing very high value petrochemicals (such as succinic acid and ethyl lactate). The overall situation can certainly improve as the bio-based products reach a higher market share. Nevertheless, the development of production costs and sale prices will depend on the future crude oil and sugar prices and on innovation in production technologies, thus making any prediction unavoidably subject to substantial uncertainties.

## 4. ENVIRONMENTAL FEASIBILITY

As shown so far, bio-based products are an important step forward in the transition process to sustainable bio-based economies[105-107] and such a transition can be closer than expected, at least from a technical point of view. Nevertheless, to ensure that adequate decisions are made and to avoid miscalculations and too optimistic claims as with first generation biofuels, it is essential to assess and quantify the potential environmental impacts of the entire process chain of bio-based chemicals, taking into consideration local production practices and boundary conditions. A common evidence is that environmental impacts could potentially be reduced by maximizing the exploitation of biomass throughout the combined production of chemicals and energy carriers, in line with the concept of an integrated biorefinery, similar to traditional petroleum refinery. The energetic and economic advantages of such a system have been extensively supported[29,108], whereas only a limited number of studies highlight the environmental perspective of biorefinery production chains with multiple output products.[109-112] The key environmental advantages of producing and using bio-based products are the significant reduction in fossil fuel use and, as a consequence, a reduction of the greenhouse gas emissions from the petrochemical industry and the downstream users.[113] Golden et al.[16] estimated that the use of bio-based products is currently displacing about 300 million gallons of petroleum per year, considering that there are two primary mechanisms by which the use of bio-based products reduces the consumption of petroleum: firstly, a direct replacement of chemical feedstocks that have traditionally been derived from crude oil refineries with chemical feedstocks now being derived from biorefineries, and secondly the increased use of natural bio-based materials as substitutes for petroleum-based materials, such as natural fibers as packing and insulating material as an alternative to synthetic foams that have been in widespread use for many years. The consumption of non-renewable energy and the consequent effect on global warming are of paramount relevance, but climate change is not the only variable to rely on: according to Rockström et al.[114], the biophysical threshold of climate system, defined by the critical value of the $CO_2$ concentration, has been crossed, but planetary boundaries were even largely overtaken in other Earth-system processes, such as biodiversity loss and interference with biogeochemical cycles, generating unacceptable environmental changes. Therefore, the impact of the bio-based chemistry should also be weighed on chemical pollution as well as on water and land use, as already highlighted by Dornburg et al.[115]

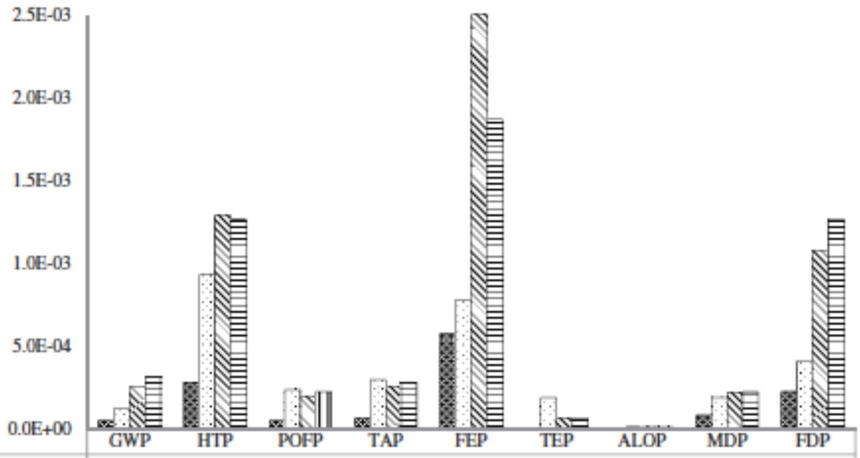
Indeed, appropriately measuring the sustainability of a bio-based chemical and comparing it to its fossil-based counterpart requires a holistic approach to introduce any claim of ‘greenness’ in the wider framework of sustainability. Several metrics are currently used to assess the sustainability of a bio-based process and, as argued by Clark et al.[67], environmental impact evaluation methodologies such as green chemistry metrics (GCMs) and Life Cycle Assessment (LCA), should become as important in measuring the sustainability of a chemical process as yield and selectivity are today and should be further developed and potentially standardized, to match every stage of a bio-based process implementation, improvement and optimization.[116,117]

GCMs include measurements of the environmental footprint of manufacturing processes, such as the atom economy and the E(nvironmental) factor among others.[118] Atom economy (AE) is a theoretical number that can be derived from the knowledge of the stoichiometric equation of the reaction(s) involved, for quickly providing a rough estimate of the amount of waste that will be generated by different processes before any experiment is performed. It is complementary with respect to the E factor (kg waste / kg product) which, conversely, provides data on the actual amount of waste produced in the process, defined as everything but the desired product.[19] Over the last two decades, the E factor has been widely adopted by the fine chemicals and pharmaceutical industries.[119] Sheldon and Sanders[120] recently proposed four metrics for the sustainability assessment of different commodity chemicals (lactic acid, 1-butanol, propylene glycol, succinic aid, acrylonitrile, isoprene and methionine): material efficiency, defined as 1 / (E + 1), i.e. the mass of products / (mass of products + mass of waste), together with energy efficiency (defined as the caloric value of the end product + caloric value of all the useful side products divided by the sum of all the fossil and renewable energy inputs), land use (defined as the amount in hectares of good agricultural soil required to produce 1 ton of product) and, finally, economics (capital costs and raw material costs per ton of product produced).

Another tool to comprehensively assess the sustainability of a product or a process is the LCA methodology[121,122], that involves the evaluation of products and processes within defined domains, e.g. from cradle-to-gate, cradle-to-grave and gate-to-gate, on the basis of quantifiable environmental impact indicators, such as energy usage, greenhouse gas emissions, ozone depletion, acidification, eutrophication, smog formation, and ecotoxicity. Since it allows to compare and benchmark the performance of a product against competing products, as well as to find hot spots in the life cycle that might require performance improvements, standardized LCA has been applied by several authors to evaluate the environmental performance of bio-based products.[104,123-127] However, the number of LCA studies that evaluate and quantify the environmental costs and benefits of bio-based chemicals is still very limited, compared to the number of LCA studies on conventional chemical products as well as biofuels.[97,128,129] A bio-based product may not automatically be synonymous with "green" and therefore using renewable feedstock is not necessarily favorable in all situations and for all environmental aspects, giving rise to several specific problems, related to the production of raw materials, such as the long-term soil fertility and biodiversity or competing land use options. Eerhart et al.[130] compared the fossil based polyethylene terephthalate (PET) and the polyethylene furandicarboxylate (PEF) based on corn starch in terms of non-renewable energy use (NREU) and greenhouse gas (GHG) emissions. Sugarcane low density polyethylene (LDPE) and polyvinyl chloride (PVC) from bio-based ethylene were assessed through their life cycle, also accounting for direct and indirect land use change[131-133], whereas Hottle et al.[134] reviewed the sustainability assessment of polylactic acid (PLA), polyhydroxyalkanoate (PHA) and thermoplastic starch (TPS), highlighting the importance of the end-of-life in the global assessment. Fully bio-based high density polyethylene (HDPE) and partially bio-based PET from Brazilian and Indian sugarcane ethanol were compared to their petrochemical counterparts produced in Europe[135]; HDPE was chosen as polymer reference for an assessment of environmental impacts of its production process from sugar beet and wheat bio-based ethanol as well as from conventional fossil routes, by Belboom and Léonard.[136] With reference to bio-based platform chemicals, the number of LCA studies is even scarcer: Cok et al.[137] evaluated the environmental performance of three different production processes of succinic acid, based on dextrose from corn, compared to the production of petrochemical maleic anhydride, succinic acid and adipic acid. Fiorentino et al.[111] focused on the impacts generated by ethyl levulinate, a derivative of levulinic acid, and glycerol from lignocellulosic residues, not only in terms of energy consumption and implications on global warming, but also in terms of human toxicity, acidification, eutrophication and photochemical oxidation potentials. Moreover, many assessments refer to bioethanol, as a biofuel rather than as a bio-based platform chemical.[97] When bio-based products are compared with their petrochemical counterparts to highlight savings and tradeoffs across impact categories, the findings may be surprising. The existing literature, although still limited to a relatively small number of LCA studies, mainly focuses on energy consumption and related global warming potential, pointing out the benefits of bio-based compounds compared to their fossil-derived equivalents. Such conclusion, although correct, disregards a huge risk for burden shift, in that benefits achieved in some impact categories may be countered by increased impacts in other categories.

Moreover, the environmental impacts of bio-based materials vary across wide ranges of values, due to the diversity of methodological choices and assumptions made in the reviewed LCA studies regarding system boundaries, functional units, life cycle scenarios or allocation procedures. Therefore, a comparison of the results reported in literature for different bio-based products is not easy and still calls for a much more standardized procedure for an acceptable comparison.

For illustrative, yet not comprehensive purposes, a comparison between ethyl levulinate from lignocellulosic residues and ester solvents from fossil sources is here proposed. In fact, levulinic acid esters, such as ethyl levulinate, may be considered potential substitutes of fossil ester solvents, such as ethyl acetate and butyl acetate, widely used in industrial production processes, even if recognized to be harmful for human health and the environment. Table 2 and Figure 6 show, respectively, the characterized and normalized impacts, quantified by means of the LCA software SimaPro 7.3.0 and the impact assessment method ReCiPe Midpoint (H) v.1.05, generated by the production process of one kilogram of bio-based ethyl levulinate, recovered via Biofine process from agricultural residues[111] and from waste woodchips[138], and of fossil-based ethyl and butyl acetates[138] on a selection of impact categories (Global Warming Potential GWP, Human Toxicity Potential HTP, Photochemical Oxidant Formation Potential POFP, Terrestrial Acidification Potential TAP, Freshwater Eutrophication Potential FEP, Terrestrial Ecotoxicity Potential TEP, Agricultural Land Occupation Potential ALOP, Metal Depletion Potential MDP, Fossil Depletion Potential FDP). Characterized and normalized impacts of bio-based ethyl levulinate from both biomass sources are much lower than impacts generated by fossil-based solvents in crucial impact categories, such as GWP, HTP, MDP and FDP. Comparable impacts were recorded for other impact categories, with impacts of bio-ethyl levulinate from agricultural residues slightly higher in POFP, TEP and ALOP. Ethyl levulinate from waste woodchips show the best environmental performance, since, differently from the case of agricultural residues, the loads of production phase (from fertilizers, in particular) are not to be charged to the supply chain. In line with the abovementioned LCA studies, non-renewable resources depletion categories (metals and fossil energy) and, consequently, global warming potential are benefited from the bio-based products, whereas the comparison of the other impact categories may be controversial, even within the very small number of recently published studies that include impact categories related to human health and ecosystem quality[134-136]. For example, the impact categories other than NREU and GHG were found to be more impacted by bio-based ethylene than by its fossil equivalent by Belboom and Léonard[136], whereas benefits on human toxicity and freshwater eutrophication are here recorded for bio-based ethyl levulinate.




| | GWP | HTP | POFP | TAP | FEP | TEP | ALOP | MDP | FDP |
|---|---|---|---|---|---|---|---|---|---|
| Bio-EL from waste woodchips | 5.072E-05 | 2.81E-04 | 4.979E-05 | 6.41E-05 | 5.77E-04 | 5.974E-06 | 9.542E-07 | 8.13E-05 | 2.24E-04 |
| Bio-EL from agro-residues | 1.22E-04 | 9.32E-04 | 2.36E-04 | 2.95E-04 | 7.80E-04 | 1.88E-04 | 1.14E-05 | 1.89E-04 | 4.09E-04 |
| Fossil-based ethyl acetate | 2.52E-04 | 1.29E-03 | 1.97E-04 | 2.52E-04 | 2.51E-03 | 6.58E-05 | 9.03E-06 | 2.22E-04 | 1.07E-03 |
| Fossil-based butyl acetate | 3.15E-04 | 1.27E-03 | 2.23E-04 | 2.79E-04 | 1.88E-03 | 6.64E-05 | 9.21E-06 | 2.23E-04 | 1.27E-03 |

Figure 6. ReCiPe Midpoint (H) normalized impacts calculated for 1 kg of bio-based ethyl levulinate from waste woodchips[138] and from agricultural residues[111] and for 1 kg of fossil-based ethyl acetate and butyl acetate[138] (according to Europe ReCiPe Midpoint (H) normalization factors).

**Table 2.** ReCiPe Midpoint (H) characterized impacts calculated for 1 kg of bio-based ethyl levulinate from waste woodchips[138] and from agricultural residues[111] and for 1 kg of fossil-based ethyl acetate and butyl acetate. [138]

| Impact categories | Unit | Bio-EL from waste woodchips | Bio-EL from agro-residues | Fossil-based ethyl acetate | Fossil-based butyl acetate |
|---|---|---|---|---|---|
| GWP | kg $CO_2$ eq | 5.69E-01 | 1.37E+00 | 2.83E+00 | 3.54E+00 |
| HTP | kg 1,4-DB eq | 1.67E-01 | 5.53E-01 | 7.68E-01 | 7.53E-01 |
| POFP | kg NMVOC | 2.65E-03 | 1.25E-02 | 1.05E-02 | 1.19E-02 |
| TAP | kg $SO_2$ eq | 2.20E-03 | 1.02E-02 | 8.67E-03 | 9.61E-03 |
| FEP | kg P eq | 2.40E-04 | 3.24E-04 | 1.04E-03 | 7.78E-04 |
| TEP | kg 1,4-DB eq | 4.90E-05 | 1.54E-03 | 5.40E-04 | 5.45E-04 |
| ALOP | $m^2a$ | 4.31E-03 | 5.15E-02 | 4.08E-02 | 4.16E-02 |
| MDP | kg Fe eq | 5.80E-02 | 1.35E-01 | 1.59E-01 | 1.59E-01 |
| FDP | kg oil eq | 3.73E-01 | 6.80E-01 | 1.79E+00 | 2.12E+00 |

More broadly, bio-based materials have been shown to lead to savings in NREU and GHG emissions in comparison to conventional materials.[139] In particular, Weiss et al.[125] calculated that bio-based materials save, on average, 55 ± 34 GJ / t and 127 ± 79 GJ / (ha∗a) of nonrenewable energy and 3±1 t $CO_2$-eq / t and 8 ± 5 t $CO_2$-eq / (ha∗a) of GHG emissions relative to conventional materials, in line with results achieved by Patel et al.[9]. On the other hand, increased impacts on human health and ecosystem quality impact categories may be generated in association with the use of fertilizers and pesticides during biomass cultivation.[125,135,140] In fact, although GHG emissions are the most commonly used metric to assess the sustainability of a product, they are correlated with other environmental impacts only when these predominantly originate from fossil fuels; LCAs that assess only GHGs and non-renewable energy consumption may miss potential unintended consequences resulting from switching from petroto bio-materials. When toxicity to humans or ecosystems and land-use are of concern, then GHG emissions alone are a weak indicator. For bio-based products, therefore, it is of paramount importance to take into consideration toxicity-related impact categories that are evidently affected by the use of agrochemicals during biomass cultivation: the agricultural phase constantly results to be more impactful than the industrial conversion steps of biomass to platform chemicals within a biorefinery context.[7,111] The viewpoint of competing land use options has also to be included in the LCAs of bio-based chemicals, in order to account for associated loss of biodiversity and ecosystem services[115,141,142], whereas a different land impact perspective was proposed by Khoo et al.[7] by measuring the land footprint as the total land area required for biomass production, thus depending also on the type of biomass selected. When LCA is applied to bio-based materials, besides the impacts of land use changes associated with biomass production, another critical issue that significantly affects the assessment results comes out to be the accounting for bio-based carbon storage. Due to the fully or partly biogenic origin of the carbon contained in bio-based materials, additional accounting methodologies are needed as compared to anthropogenic carbon emissions generated from sources such as the burning of fossil fuels. There are two fundamental approaches that can be used:

1. The carbon uptake is accounted for as an initial negative emission and the carbon is considered to be stored for a period of years. Afterwards, the positive emission from the later burning or decomposition is added in the life cycle inventory.
2. Biogenic emissions can be assumed as carbon neutral and are consequently excluded from life cycle inventory.

Which approach is more appropriate is currently being debated in the scientific community.[143,144] The advantage of temporarily storing carbon depends on the analytical time horizon over which the GWP is calculated (typically 100 years): benefits would generally be greater for short analytical time horizons and decrease as the time horizon increases, since emissions are only delayed.

As pointed out by Pawelzik et al.[126], the current ISO standards[121,122] provide principal methodological guidance, but no detailed instructions on how to address such issues, thus generating a weakness for the lack of commonly-used, widely-shared, and scientifically-sound methodologies.

The lack of a comprehensive insight into the environmental impacts of production, use and disposal of bio-based materials may weaken the viability and acceptability of bio-based products by stakeholders and consumers, leaving some aspects unaddressed and choices not sufficiently supported by clear evidence of environmental benefits. The aim of a reliable sustainability assessment should be to provide an integrated analysis, capable of generating a useable set of recommendations for the development of Product Category Rules (PCRs) and Environmental Product Declarations (EPDs) (http://www.environdec.com), supported by a quantitative approach capable of highlighting the improvement or worsening of the analysed systems in relation to the generated environmental impacts over selected impact categories, at different time and spatial scales. Moreover, the release of PCRs and EPDs would provide the produced bio-based materials with a clear set of characteristics thus allowing their certification, eco-labelling, marketing, acceptance and capacity to comply international and European regulations (e.g. REACH).

## 5. CONCLUDING REMARKS

This survey of biomass value chains and conversion pathways sheds some light on different aspects of the envisioned transition from a petroleum to a biomass-based chemical production. Firstly, the technical aspects of such a transition have been and still are under constant investigation. Technological advancements have been and are continuously being achieved and, although some challenges still remain unsolved, technology does not seem to be a constraint for future market implementation of a bio-based chemistry. On the other hand, energetic, economic and environmental feasibility of biomass value chains still need to be thoroughly assessed. In several competing routes to the same product, the economic drivers for an effective transition to a more sustainable chemical production depend on existing infrastructure, feedstock costs, feedstock availability as well as the efficiency of the relevant process technology. At the same time, there are environmental drivers and, in the wider sense, sustainability drivers for the selection of different process alternatives. Biomass conversion processes can be energy intensive and their impacts surprisingly high in different environmental compartments, thus calling for a careful evaluation of environmental loading generated and actual benefits achievable. The use of environmental assessment tools, such as LCA, has demonstrated to be crucial in making the right choices of the available feedstocks and alternative technologies: the raw material production is the dominant step in the life cycle of a product and, as a consequence, the use of technologies that provide improved conversion efficiency has to be preferred in order to increase the environmental benefits of bio-based products. In fact, the aptitude of LCA to highlight hotspots of processes allows for the identification of strategies to be adopted in the specific contest, in order to maximize the optimization potential of biomass exploitation. Nevertheless, to routinely assess the sustainability of bio-based products and processes and to define a roadmap of technically and environmentally feasible options will require more robust and transparent environmental life cycle inventory databases, a more standardized calculation and assumption-making procedure as well as better modeling and understanding of the social and economic aspects of sustainability and their relationships to technological aspects.

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# CHAPTER 2 – WASTEWATER TREATMENT

## Energy efficiency and recycle patterns scenarios for urban wastewater and sewage sludge treatment.

*Introduction*

The world is facing a water quality crisis resulting from continuous population growth, urbanization, land use change, industrialization, food production practices, increased living standards, unsustainable water use practices and wastewater management strategies. Wastewater has a direct impact on the biological diversity of aquatic ecosystems and its inappropriate management is capable of disrupting the fundamental integrity of life support systems, on which a wide range of sectors, from urban development to food production and industry, depend (UNWATER, 2015).

In this context, wastewater treatment (WWT) facilities are of vital significance for urban systems. It has been acknowledged that wastewater management clearly plays a central role in achieving future water security in a world where water stress is likely to further increase (OECD, 2012). While being crucial for pollutants removal and reusable water supply, WWT consumes resources and triggers environmental emissions during a plant lifetime (Shao et al., 2014). Urban wastewater management requires large material, energy, economic and technological investments for the construction and operation of treatment plants. Energy consumption in WWT plants and the related greenhouse gas (GHG) emissions are also steadily increasing due to strict treatment requirements.

A crucial aspect of WWT is represented by the management of sewage sludge. Sludge is an unavoidable by-product of WWT and may hold many toxic substances such as pathogens, heavy metals and organic contaminants, which can cause serious environmental pollution. The management of this by-product is still a challenge especially in developing countries, due to the lack of clear regulation, lack of a methodology for selecting a suitable sludge management system and high investment and operation cost for refurbishing (upgrading) old WWT facilities. Given the need to achieve long-term sustainability, the objectives of urban water systems need to go beyond the protection of public health and receiving bodies, and also focus on strategies to reduce the impacts on natural resources, to optimize the use of energy and water and reduce waste generation.

A step ahead toward more sustainable procedures requires the identification of management routes capable of maximizing recycle and recovery benefits through low energy impact systems and development of operational systems appropriate to local circumstances (Spinosa et al., 2011). The optimization of system processes, the upgrade to more efficient technologies, and the improvement of energy management, and energy generation within the WWT plants (i.e., sludge digestion with biogas production and reuse, sludge gasification for syngas generation and use) are possible ways to lower energy consumption and environmental impacts as well as to achieve energy self-sufficiency.

Nonetheless, it is crucial to evaluate the effectiveness of such implemented options in terms of reduction of resources consumption, waste, and emissions. Indicators of efficiency and environmental performance are fundamental to marking progress toward more sustainable patterns of human development (Brown et al., 2012).

Life cycle assessment (LCA) is a valuable tool that can be used to evaluate the environmental impacts associated to WWT plants (Guest et al., 2009). LCA investigates the environmental impacts of systems or products from cradle to grave throughout the full life cycle, from the withdrawal, refining and supply of materials and fuels, through the production and operation of the investigated objects, to their final disposal or recycling (Rebitzer et al., 2004).

In this paper LCA is used to compare the environmental performance of different scenarios for sludge management in a WWT plant located in the municipality of Nocera Superiore, in the province of Salerno, Southern Italy. The different scenarios aim at decreasing the amount of sludge disposed of in landfill as well as at increasing the energy efficiency of the different process steps via increased recycling of still usable waste resources. The alternatives chosen have been selected according to the potentialities of the investigated WWT plant and those of the area where the WWTP evaluated is located.

*The investigated system*

The investigated WWT plant is located in Nocera Superiore, a municipality of Campania Region, Southern Italy. It is a modern and centralized plant exploiting the most wide-spread technology in Europe, i.e. the advanced activated-sludge process. This technology is able to achieve very high pollutants removal efficiencies, and therefore it is widely-applied to treat urban wastewater worldwide. On the other hand, the operation of such systems is cost and energy intensive, mainly due to the aeration and sludge treatment associated processes. Additionally, despite effective sludge treatment should include dynamic thickening, belt press dewatering, anaerobic digestion with biogas recovery and heat drying, the sludge treatment in this WWT plant is poorly performed. This is due to the fact that anaerobic digestion and heat drying treatment steps are not in operation for technical and administrative reasons. The resulting wet sludge cannot be disposed of in Campania Region due to environmental concerns. For this reason, the wet sludge is transported to Puglia Region for disposal in a controlled sanitary landfill (the average transportation distance is 200 km), causing further environmental and economic costs. For these reasons, the Nocera Superiore WWT plant was particularly suited to be chosen as case-study to perform a careful evaluation of the environmental benefits achievable by means of innovative management strategies aimed at decreasing the amount of waste disposed of as well as at increasing the energy efficiency of process steps.

In particular, four scenarios for wastewater and sewage sludge treatment are considered in this study (Fig. 2.1a–d). The first scenario (scenario A business-as-usual, hereafter BAU) is based on the WWT processes actually performed in the WWT plant of Nocera Superiore: after mechanical treatment, dewatered sludge is transported by truck to a landfill for final disposal, while treated water is released to a river. The second scenario (scenario B) assumes the anaerobic digestion of sewage sludge with biogas recovery within the WWT plant and its use for cogeneration of heat and electricity. As the investigated WWTP is already equipped with a two-stage mesophilic digester, the mesophilic fermentation of sludge was chosen as the technology to be evaluated. Anaerobic digestion consists of a series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen. In such a process biogas is produced in anaerobic tanks where sludge is mixed and maintained at a temperature of 30–40◦C, in order to optimize bacterial activity (Jungubluth et al., 2007). The recovered biogas is then used for heat and electricity cogeneration. Electricity is fedback to the WWT process, in order to lower the huge demand for grid power. Heat is used for downstream thermal drying of digestate to lower its mass and make transportation less energy expensive. Moreover, while wet sludge cannot be disposed of in Campania region, dry sludge disposal in local landfills is allowed. As a consequence, transport distance to landfill decreases to 30% of the distance in scenario BAU. Thermal drying of digestate also benefits from the use of heat from WCO collected from restaurants, hotels and agro-food industry in Campania Region. WCO is collected and transported to a treatment plant where it is mechanically pre-treated to lower the content of solid waste by means of decantation and centrifugation. The purified WCO can be directly burnt to produce energy or used as a useful feedstock for biodiesel production (Ripa et al., 2014). In this study the recovered WCO is combusted for heating purpose, i.e. thermal drying of digestate. The amount of used WCO is assumed to be a fraction of the total WCO collected in Campania Region calculated according to the population equivalents (PE) of the WWT plant (300,000 PE). WCO covers 15% of the total energy demand of thermal drying of digestate, while about 55% is covered by the use of biogas from anaerobic digestion. The residual energy demand (about 30%) is supposed to be met by the use of purchased methane. The third scenario (scenario C) suggests a furtherly circular pat-tern: the sludge is dried and the residual mass is gasified. Syngas is added to previously produced biogas for heat and power cogeneration. The heat and electricity generated are fedback to the WWT plant. Heat produced from syngas is used for the thermal drying of sludge. This feedback of heat avoids the use of the methane required in scenario B. In so doing, thermal drying of digestate is totally performed by utilizing heat produced within the WWT plant. The feedback of electricity further lowers the demand for grid power of BAU scenario. A very small residual fraction of digestate is landfilled. The fourth scenario (scenario D) is drawn on the same assumptions as scenario C except for the final disposal of wastewater. In all previous scenarios, treated wastewater is released to a nearby river, with discharge within the law limits. Scenario D is based, instead, on a pioneering bioenergy production system investigated in Sweden by Buonocore et al. (2012), integrating wastewater treatment and willow

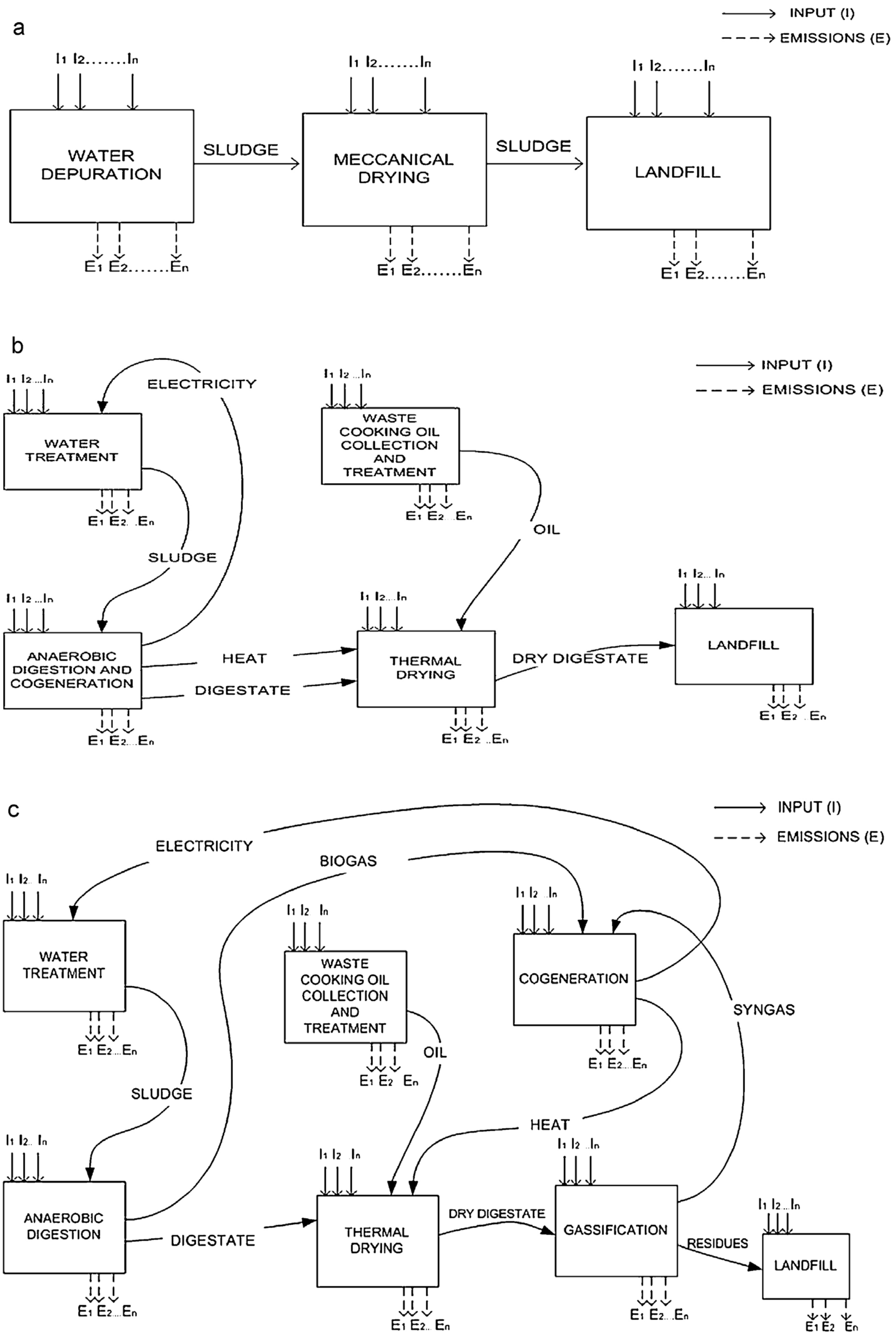
(Salix Viminalis) farming. The Mediterranean climate of Campania Region is suitable for willow production. Furthermore, as pointed out by Fahd et al. (2012), by combining statistical data about available land in Campania Region in 1985 with data regarding the agricultural and polluted land and the urbanised areas in2006, there are about 150,000 ha of marginal land abandoned or set aside since they do not provide enough income to the farmer. As a consequence, their hypothetical use for an energy-oriented system linked to the WWT would not compete with food production. In this context, scenario D assumes that almost 50% of the treated wastewater volume is not discharged into surface waters but it is used for irrigating willow cropped on marginal land (about 1150 ha) in the same area where the WWT plant is located. The amount of wastewater needed is estimated by taking into account land availability, nutrients content in wastewater, and water and nutrients requirements of willow during the growth season (May–October) (Guidi et al., 2008). The residual amount of treated wastewater is assumed to be released to a nearby river.

Since willow can uptake 75–95% of nitrogen and phosphorusin wastewater, the annual wastewater load can easily meet the requirements of willow in terms of water and nutrients. Irrigation with nutrient-rich water would promote plant growth, thus resulting in high biomass yield (7.2 t dry mass/ha). Willow is harvested and delivered to a Combined Heat and Power plant for cogeneration of heat and electricity. A fraction of the generated electricity (~30%) is supposed to be fedback to the WWT plant thus preventing the demand for grid power. The remaining fraction of electricity generated by the CHP plant (around 70%) would be supplied to local industrial and/or domestic users and it is considered as an avoided burden to the regional system in which the WWT system is embedded. In order to include the benefits provided by the virtuous use of local biomass for electricity generation, the scale of interest is expanded to include the entire regional area. This choice allows to account for the advantages due to the electricity that is not fed back to the plant and that would not be considered in the results if only the plant scale is considered. Furthermore, scenario D is compared with a renewable scenario (scenario E) assuming that the electricity used in the BAU scenario is met by renewable sources. The assumption is based on data available from the Enel Green Power that is a society of the Enel Group developing and managing energy generation from renewable sources at a global level and present in Europe, Americas, Asia and Africa. The "EnelGreen Power" mix adopted in this scenario is based on the renewable power installed in Italy. It includes 49.9% of hydroelectric, 23.8% of geothermal, 23.7% of wind and 2.6% of solar.

LCA was used to compare the environmental performance of these different scenarios. The ReCiPe was chosen among the LCIA methods. The treatment of 1000 m3of wastewater was chosen as functional unit (FU). All materials, emissions, cost, energy consumption, and recovery levels are referred to this amount of treated wastewater.

This LCA analysis can be defined as an expanded "gate to gate" study, since the perimeter fences of the investigated WWTP were set as the physical system boundaries of the directly analyzed construction and operation phases, while for the processes production of chemicals, electricity, construction materials, waste disposal, transportation, anaerobic digestion, gasification and fertirrigation, the system

boundaries were expanded by using case studies from the Ecoinvent database and scientific literature.
The performed LCA study covers the actual processes associated to wastewater treatment, including:
•the construction phase and production of construction materials,
•the operation and maintenance (O&M) phase,
•the treatment performed within the WWTP, the transportation and final disposal of sludge, grit and screening waste.
Finally, the decommissioning phase is excluded from this study due to insufficient data pertaining to such a phase.


a
INPUT (I)
EMISSIONS (E)
WATER DEPURATION
SLUDGE
MECCANICAL DRYING
SLUDGE
LANDFILL
b
INPUT (I)
EMISSIONS (E)
ELECTRICITY
WATER TREATMENT
SLUDGE
ANAEROBIC DIGESTION AND COGENERATION
HEAT
DIGESTATE
WASTE COOKING OIL COLLECTION AND TREATMENT
OIL
THERMAL DRYING
DRY DIGESTATE
LANDFILL
c
INPUT (I)
EMISSIONS (E)
ELECTRICITY
BIOGAS
WATER TREATMENT
SLUDGE
ANAEROBIC DIGESTION
DIGESTATE
WASTE COOKING OIL COLLECTION AND TREATMENT
OIL
COGENERATION
SYNGAS
HEAT
THERMAL DRYING
DRY DIGESTATE
GASSIFICATION
RESIDUES
LANDFILL

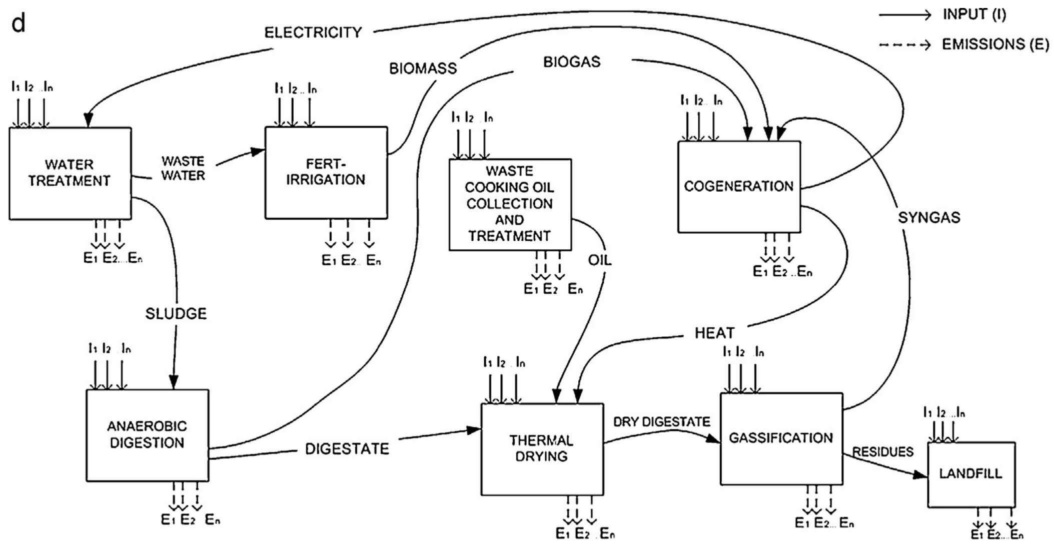



**Figure 2.1**. Flow diagrams of scenarios investigated for sewage sludge treatment: (a) scenario A, business as usual − BAU; (b) scenario B, (c) scenario C; (d) scenario D. ScenariosB–D differ from scenario A according to increased implementation of circular patterns (recycling of still usable energy content of sludge or external waste resources).

*Results*

The life-cycle contribution per 1000 $m^3$ of wastewater (FU) to selected impact categories in the investigated scenarios is displayed in Table 2.1. The characterized impacts of the scenarios are shown as percentages in Figure 2.2, where the potential improvements achievable in scenarios B–D are compared to the results of scenario A (put conventionally at 100%). Results show that the contributions to the chosen impact categories decrease in all the scenarios when compared with the BAU scenario. Scenarios B and C reduce the contribution to the Global Warming Potential (GWP) by 9% and 35% respectively, while the contribution to Fossil Depletion Potential (FDP) is lowered by 9%and 36%.

**Table 2.1**. Total contribution of the four scenarios to the selected impact categories.

| Impact category | Reference unit | Scenario A | Scenario B | Scenario C | Scenario D |
|---|---|---|---|---|---|
| Climate change GWP100 | kg CO2-Eq | 620.64 | 593.92 | 404.27 | 1.93 |
| Fossil depletion FDP | kg oil-Eq | 101.95 | 92.39 | 64.95 | -43.90 |
| Freshwater eutrophication FEP | kg P-Eq | 0.84 | 0.83 | 0.81 | 0.34 |
| Human toxicity HTPinf | kg 1,4-DCB-Eq | 198.70 | 160.82 | 108.76 | 93.17 |
| Particulate matter formation PMFP | kg PM10-Eq | 0.49 | 0.40 | 0.37 | 0.12 |
| Photochemical oxidant formation POFP | kg NMVOC | 1.18 | 0.90 | 0.77 | 0.41 |
| Terrestrial acidification TAP100 | kg SO2-Eq | 1.25 | 1.02 | 0.98 | -0.020 |

The contribution to other impact categories, as Human Toxicity Potential (HTP), Particulate Matter Formation Potential (PMFP) and Terrestrial Acidification Potential (TAP), is also lower compared to the BAU scenario (Figure 2.2). The Freshwater Eutrophication Potential (FEP) does not substantially change in scenarios B and C while it results 53% lower in scenario D compared to the BAU scenario. Scenario D is also capable of reducing HTP by almost 60%. All the other categories also benefit from this scenario (Figure 2.2).

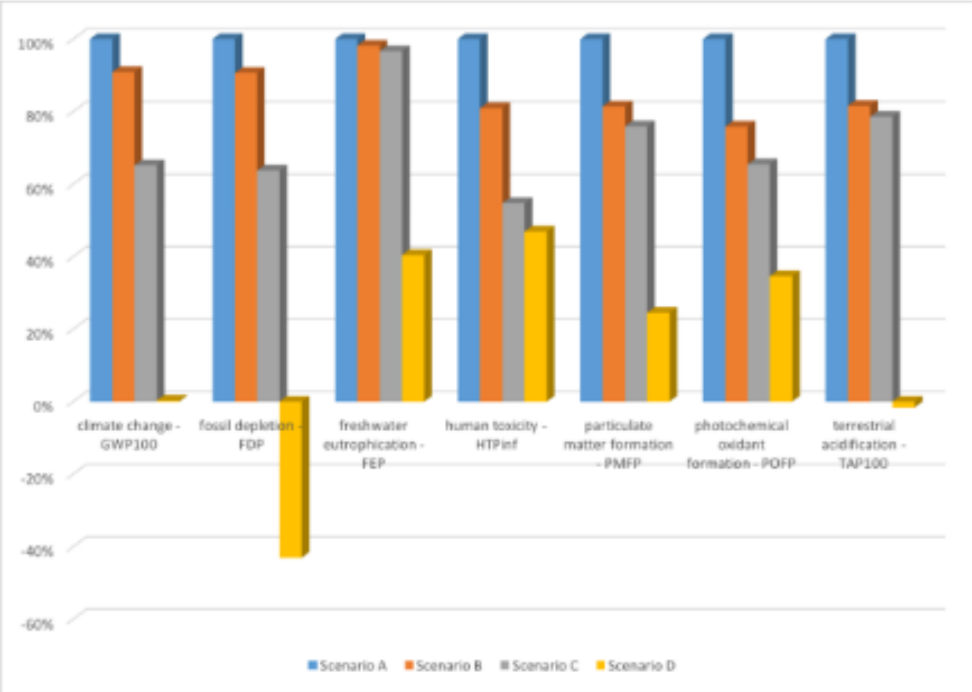



**Figure 2.2.** Characterized impacts of the four scenarios

Figure 2.3 shows the normalized impacts of the four scenarios. The most impacted category results to be the FEP in all the scenarios. The second most impacted category is HTP. Still, scenario D results the most valuable option for reducing the contribution to both these impact categories. The characterized impacts of scenario D are also compared to those of the renewable scenario—scenario E (put conventionally at100% in Figure 2.4). Results show that scenario D has higher potential for abating the contribution to environmental impacts categories even when a green mix is assumed to be used within the WWT plant. The comparison between normalized impacts of scenario D and the renewable scenario (Figure 2.5) confirms that the scenario D would be more capable of reducing the impacts in most of the selected categories (i.e., FEP and HTP) compared to the choice of an electric green mix for powering the WWT plant (that is, anyway, a better choice than the BAU scenario).

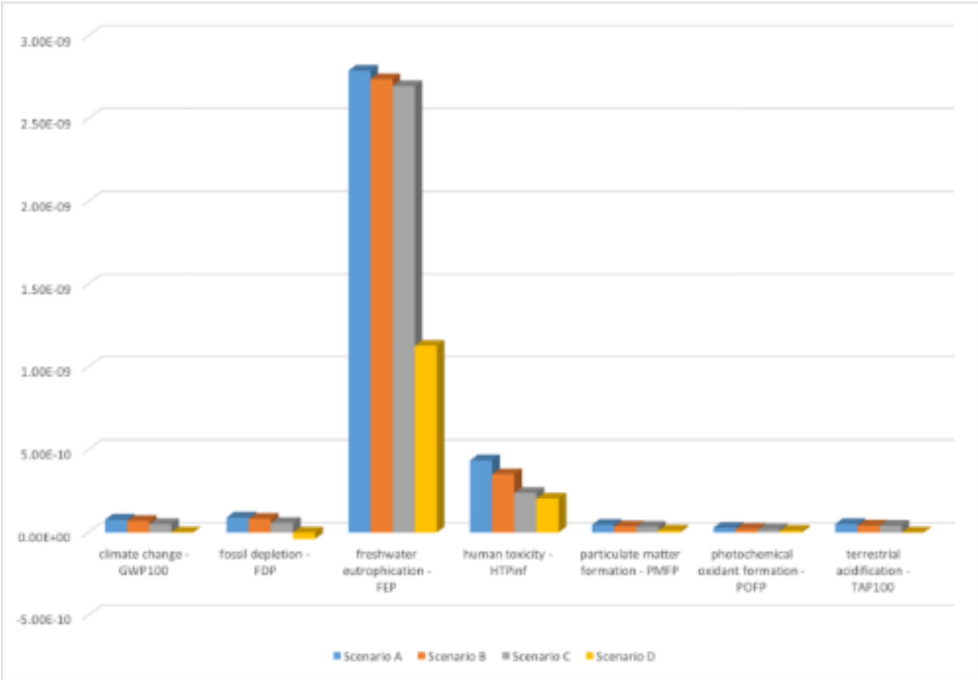



**Figure 2.3.** Normalized impacts of the four scenarios to impact categories.

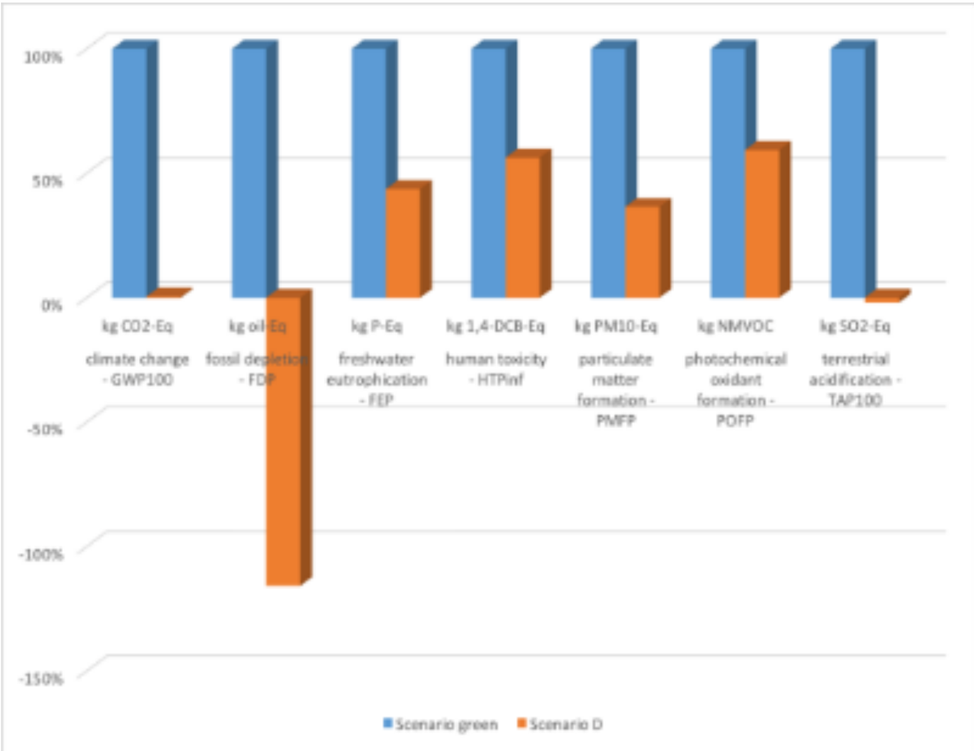



**Figure 2.4.** Comparison between characterized impacts of the green mix Scenario and Scenario D.

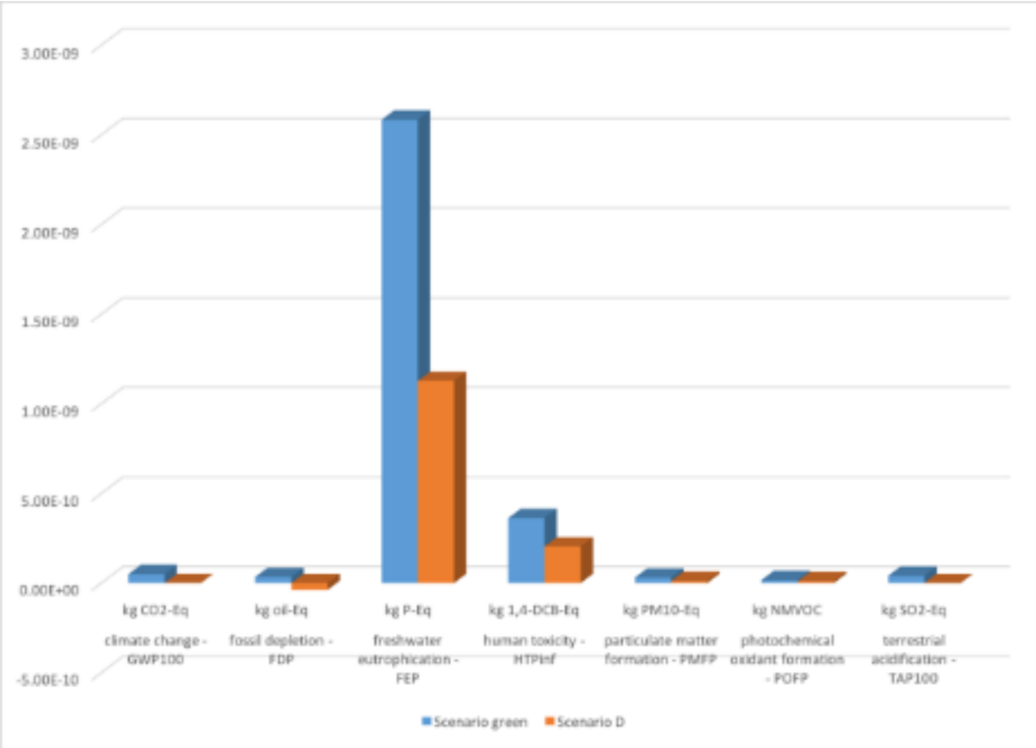



**Figure 2.5.** Comparison between normalized impacts of the green mix Scenario and Scenario D.

*Discussion*

The investigated scenarios are oriented towards achieving the energy self-sufficiency of the investigated WWTP, decreasing other impacts not directly involving energy supply, and at the same time, sensibly reducing the amount of waste to be transported and disposed of. Energy production from sewage sludge (i.e. biogas and syngas production) is an important energy source, capable to sensibly reduce plant's dependency on fossil resources, thus mitigating its energy-related environmental burdens. To this end, the combined application of anaerobic digestion, dehydration and gasification has proved to be one of the most promising technologies in terms of both energy recovery and sludge mass reduction (Lacroix et al., 2014; Cao and Pawlowski, 2013). The latter gain is also noteworthy, as the delivery and disposal of sludge have resulted to be among the most important contributions to the environmental profile of WWTPs (Corominas et al., 2013). Also the reuse of recovered WCO within the WWTP represents an additional step towards closing the local resource circle by linking the treatment of different kinds of municipal wastes, i.e. wastewater, its by-products and waste cooking oil generated from households and restaurants (of course, WCO inclusion requires a boundary expansion to also account for the WCO collection and treatment). In the last scenario, additional interesting benefits are coupled with the possibility to reuse wastewater for irrigation of energy crop fields, in order to provide biomass for energy purpose. This solution manages not only to further minimize plant's dependency on fossil fuels, but also to sensibly reduce the volume of treated wastewater to be discharged in receiving water bodies. Among the investigated scenarios, the best environmental performance was achieved in scenario D that represents a circular pattern where a) sludge is not disposed in landfill but further processed to generate biogas and syngas and b) the volume of treated wastewater is not completely discharged into surface waters but partially reused for fertirrigating willow fields for biomass production and electricity generation. The negative value for the fossil depletion and the terrestrial acidification categories resulting for scenario D are due to the avoided impacts associated to the cogeneration of heat and power (CHP) from willow biomass fertirrigation by means of nutrients in wastewater. The energy generated is much greater than the power demand of the WWT system so that the avoided impact refers to the avoided use of grid electricity by the territorial system. The latter, in fact, benefits from the surplus electricity and heat cogenerated by using willow biomass. The use of wastewater for irrigation and fertilization of willow cropped land allows non-negligible energy savings and contributes to renewable energy generation, but is only feasible if land is avail-able at short distance from the WWT plant. This requires that WWT plant designs are made considering this option into account since the very beginning. As a result of this “towards zero-emission” oriented production pattern, where waste generated by a process can be used and upgraded as input to support another process, the overall generation of waste and emissions decreases significantly. Such a perspective should represent a valuable option for a sustainable management of wastewater and sewage sludge. The FEP resulted the most impacted category in all the scenarios. This finding is due to the high content in nitrogen and phosphorus in wastewater mainly deriving from human and agro-industry waste. Wastewater discharges are understood to make a significant contribution to the problems of eutrophication and scenario D seemed to be a valuable option for reducing the nutrient pollution of surface waters. The abatement of the eutrophication impacts in scenario D is due to the utilization of wastewater for growing willow crops that avoids the discharge of nutrients rich treated water into the river. However, the amount of wastewater supposed to be used for fertirrigating willow fields only amounted to about 50% of the total annual volume generated by the WWT plant. HTP was the second impacted category. The high contribution to human toxicity is associated to sludge disposal in landfill. The contribution to the HTP decreases from scenarios A to D since their circularity allows the recycling of sludge within the WWT plant thus reducing the amount landfilled. Scenario D resulted to be the best option also in abating the HTP burden. However, the advantage due to the generation of electricity from local fertirrigated willow biomass is partially offset by wood combustion that also contributes to HTP. In order to overcome this last problem, scenario D could be complemented by the use of an appropriate fraction of wood biomass for platform chemicals instead of combustion. Fiorentino et al. (2014) demonstrated that if wood biomass is processed in a bio-refinery context, by selecting appropriate feedstock and technology suitable for the utilized raw materials, bio-based products actually generate higher environmental and economic benefits than an energy-oriented pattern. Such alternative was also not integrated in this study (as it would require an optimization of the wood fraction allocated to CHP and the wood fraction allocated to the chemical route) but it would certainly be interesting for future studies to explore the potential mitigation of environmental impacts that could be achieved over this new pattern. Finally, a green electricity mix supplied by the national electric company ENEL is supposed to be used within the WWT plant (scenario E). Conventional electricity generation is a significant source of greenhouse gas emissions. The emissions from conventional electricity generation contribute to a number of serious environ-mental problems, including acid rain, fine particulate pollution, and climate change (EPA, 2010). Green power generates less pollution than conventional power and produces no net increase in greenhouse gas emissions, helping protect human health and the environment. In this study the adoption of a renewable electricity mix was an important option, although not capable of significantly reducing the impact to eutrophication and human toxicity as does scenario D.

*Conclusions*

Life cycle assessment allowed to compare the environmental performance of different scenarios for wastewater and sludge management, characterized by different degrees of recycling within the plant as well as at larger regional scale.

Results showed that the most desirable option would be a circular pattern where a) sludge is processed to generate biogas and syngas to be further combusted for the generation of electricity and heat, b) collected and refined waste cooking oil from the surrounding area is used as additional heat source, and c) wastewater is used to fertirrigate wood crops for bioenergy purposes.

The circularity adopted in this Scenario decreases the overall environmental impacts of the WWT plant, allows the plant to be totally energy self-sufficient and contributes to (although small) renewable energy generation.

Treated wastewater supports biomass fertirrigation that can be used together with other bio-wastes (such as waste cooking oil) to produce energy, nulling plant’s power requirement and even creating additional income through the sale of surplus energy to the local grid.

It is evident from the investigated case study that new and improved processes and technology are capable to generate opportunities for impact reduction in WWT plants, but each option needs to be carefully evaluated over the entire life cycle, according to the particular context in which the WWT plant is located.

Further improvements of the wastewater and sludge management could be implemented by adopting additional circular strategies at larger scale, after careful LCA evaluation. Results clearly show, however, that an improved wastewater treatment plant should not be considered a potential energy source (in spite of the biogas and syngas generation and additional biomass production) but instead a self-sufficient facility providing the much more important water treatment service at low or no energy cost. The biomass energy production becomes a tool for and a co-product of the abatement of water eutrophication potential, requiring a large land availability and occupation for this to happen. When marginal land is available, the WWT plant and its improved circular features may provide additional benefits, which calls for preliminary eco-design and appropriate siting of the plant within the urbanized area that releases the wastewater and enough rural area to receive the treated water and allow biomass cropping.

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# CHAPTER 3 – WASTE-TO-ENERGY PLANTS

Energy efficiency and clean energy have been recognized as key factors to minimize the cost and negative effect of climate change on the environment and society (EU, 2006). The energy sector is the largest contributor to GHG emissions (Eurostat, 2012), and for this reason, strategies to reduce the emissions from this sector are a key point of climate change mitigation strategies (Evangelisti et al., 2015). Waste contains fossil derived materials such as plastics. Moreover, it also contains biogenic materials such as paper, card and food waste. All of these fractions can be potentially converted into energy. The implementation of waste-to-energy (WTE) supply chains was suggested as a suitable method for energy production from waste, in order to deal simultaneously with human security, pollution, and, last but not least, energy recovery.

This Chapter, dealing with energy recovery from waste as well as efficiency of waste-to-energy processes, includes:

*Chapter 3.a Recycling Waste Cooking Oil into Biodiesel*

*Chapter 3.b Power generation from animal by-products*

# Chapter 3.a Recycling Waste Cooking Oil into Biodiesel

## Introduction

The European Directive 2009/28/EC, establishing a substitution corresponding to 10% of biofuels in the total consumption by the year 2020 (EC, 2009), generated an emerging interest in replacing fossil feedstock with biomass-based raw materials. In order to comply with this priority, the production of biodiesel from waste cooking oil (WCO) and the environmental loads associated to this conversion process have been evaluated. Biodiesel is a diesel fuel defined as mono-alkyl esters of vegetable oils or animal fats. It is recommended as a substitute for petroleum-based diesel mainly because of its claimed renewable nature. The use of WCO as a biodiesel feedstock has been identified as an alternative source of fatty materials for the production of biofuels (Canakci and Van Gerpen, 2003). WCO is a domestic waste generated from households and restaurants, as the result of using edible vegetable oil for cooking and frying. WCO causes hard negative environmental impacts caused by the uncontrolled disposal of such products. Diverting WCO from improper disposal extends the product life cycle and prevents the contamination of groundwater supplies with this harmful liquid waste: very often, this residue is poured in sanitary sinks and toilets, going to stop in the sewer systems causing damages in the clogging of the pipes and increasing the price of the processes of the stations of treatment, causing the pollution of the aquatic environment. As a consequence, collecting and recycling WCO contributes to solve simultaneously three environmental problems: waste reduction by product reuse/recovery, reduction of the fossil fuels energy dependence and reduction of pollutant emissions. Energy production from wastes such as WCO to produce diesel-like oil is not only a solution to the waste disposal problem but is also a mean to recover the valuable energy content of waste stream. The present work is based on case study data about collection, sorting, recovery and treatment phases of WCO in Campania Region.

*Materials and Methods*

The environmental assessment was performed according to the Life Cycle Assessment methodology, described in the standards ISO 14040 and 14044 (ISO 2006a, b). In this study, LCA methodology is used as a tool for the comparative evaluation of diesel production by using fossil resources, biomass and alternatively, WCO, as raw materials. As a further step, a deep analysis of each process phase is performed in order to offer suggestions for process improvement that would promote an increased efficiency of WCO treatment.

Goal and scope

The goal of this study is, firstly, to compare different options for biodiesel production and, secondly, to analyze the production steps of biodiesel from WCO under an environmental perspective. At this aim, an attributional LCA was performed in order to illustrate the environmental impacts of the analyzed process. The functional unit chosen for this assessment is one kilogram of diesel/biodiesel produced. In the presence of two or more intermediate or final products (e. g. biodiesel and glycerine delivered by trans-esterification phase), an economic allocation is pursued. The allocation by economic value is based on average market prices of final products (http://www.alibaba.com). In this study WCO is considered as a waste stream. In so doing, the agricultural production of oil is not included, according to standard procedure for the life cycle of waste (Sundqvist, 1999; Ekvall and Finnveden, 2000; Bjarnadóttir et al., 2002). The approach used in this analysis is 'from gate to gate'. The environmental loads associated with the use of biodiesel are not taken into account, since they do not have any influence on the comparative study of different production systems. The system under examination consists of four stages (Figure 3.1): 1) collection of WCO, 2) pre-treatment, 3) delivery of treated oil to the biodiesel facility and 4) its conversion into biodiesel through trans-esterification. WCO is firstly collected in plastic containers of different capacities from restaurants, hotels and agro-food industry by Papa Ecologia S.r.l. (Campania Region, Italy). Then, WCO is supplied to a pre-treatment company (Proteg S.p.A, Campania Region, Italy) and mechanically pre-treated to lower the content of solid waste by means of decantation and centrifugation. The purified WCO is transported by truck to a biodiesel production plant (DP Lubrificanti, Lazio Region, Italy). The final stage is the trans-esterification reaction of the triglyceride with an alcohol (methanol) in the presence of a catalyst, yielding a mixture of fatty acid alkyl esters (biodiesel) and glycerin.

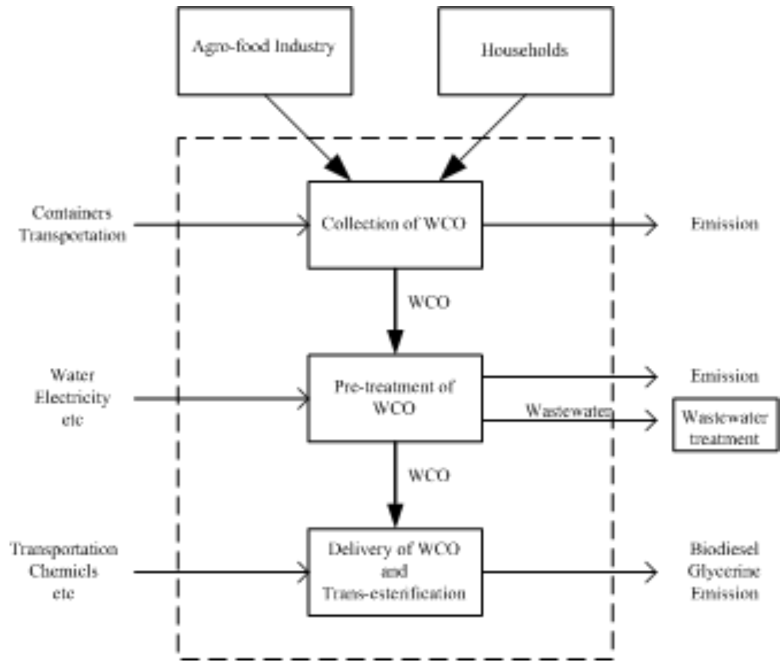


**Figure 3.1**. Schematic flowchart of the WCO system.

Life cycle inventory (LCI)

The Life Cycle Inventory (LCI) is a crucial step, since the quality of the whole study depends on the representativeness, consistency, accuracy and geographical specifications of the data collected, in accordance with the ISO 14040 standards. In the inventory phase, information is gathered as inputs and outputs for all the processes involved in the system under study. The inputs and outputs for each stage have been obtained from different sources. Primary local data were personally communicated by Papa Ecologia S.r.l. and Proteg S.p.A. They refer to a process survey made in year 2012 for the above-mentioned phases (collection and purification); adjusted average industrial operational inputs from Ecoinvent v. 2.2 database are used for the trans-esterification phase instead of those specific for DP Lubrificanti S.r.l. in the nearby Lazio Region, due to incomplete inventory information. Wastewater treatment and related environmental impacts are also included in the analysis. Fuels, machinery, water, electricity, process chemicals, plant construction materials for the industrial conversion phase as well as the main intermediate and final products are shown in Table 3.1. All the values are calculated with reference to a functional unit of 1 kg of biodiesel produced over one year.

**Table 3.1**. Inventory of input flows to collection, pre-treatment and trans-esterification phases (unit/kg/yr).

| INPUT FLOWS | VALUE | UNIT |
|---|---|---|
| **Collection phase** | | |
| Diesel[1] | 3.34E-02 | kg |
| Truck (van<3,5 t)[2] | 6.07E-02 | t*km |
| HDPE (WCO container) | 1.16E-02 | kg |
| **Pre-treatment phase** | | |
| Building, hall | 1.93 | $m^2$ |
| Steel (pipeline and centrifuge), low-alloyed | 6.40E-05 | kg |
| Electricity, medium voltage[3] | 2.47E-02 | kWh |
| Liquid storage tank | 9.52E-08 | item |
| Pump | 2.26E-05 | item |
| Water | 1.19E-02 | kg |
| Sodium hypochlorite, 15% in $H_2O$ | 1.18E-08 | kg |
| Wastewater treatment plant[4] | 4.89E-11 | item |
| **Trans-esterification phase** | | |
| Transport, lorry > 32t [5] | 0.22 | t*km |
| Heat, natural gas, at industrial furnace | 0.99 | MJ |
| Methanol | 0.12 | kg |
| Posphoric acid, 85% in $H_2O$ | 4.97E-03 | kg |
| Potassium hydroxide, at regional storage | 1.22E-02 | kg |
| Water | 2.92E-02 | kg |
| Electricity, medium voltage | 4.08E-02 | kWh |
| Vegetable oil esterification plant[6] | 1.01E-09 | item |
| Treatment sewage to wastewater treatment plant | 6.75E-05 | $m^3$ |
| **FINAL PRODUCTS (all phases)** | | |
| Collected oil | 1.34 | kg |
| Purified oil | 1.11 | kg |
| Biodiesel | 1 | kg |
| Glycerin | 0.11 | kg |

[1]Diesel is an input of the operation process in the truck.

[2]Truck includes also the van and road maintenance and disposal. It includes also the local emission delivered by engine combustion.

[3]For electricity, the reference is to the Italian production mix of medium voltage electricity.

[4]Wastewaster treatment plant is considered in the analysis based on the typology of the analyzed plant. All local emissions are also included in the analysis.

[5] The transport covers the distance Caivano-Aprilia (200 km) and includes the diesel consumption and the local emissions. Due to the lack of specific data, the diesel consumption is referred to operation process, transport, lorry>32t in the Ecoinvent database.

[6] Due to the lack of specific data, an average industrial vegetable oil esterification plant is used as reference.

## Life Cycle Impact Assessment (LCIA)

Comparative LCIA has been carried out with reference to biodiesel from rapeseed and fossil diesel: key data for the quantification of inputs (chemicals, water, electric and thermal energy demands, etc.) and outputs were derived from Ecoinvent database. Background data over the supply chain of energy and materials are derived from Ecoinvent Unit Processes library (Ecoinvent, 2010), which comprises complete upstream processes (e.g., energy supply and raw materials extraction), including infrastructures (e.g., means of transportation or pipelines). Materials and energy carriers are selected within the database from processes and geographical areas as similar as possible to the Campania Region. Worldwide production mix is chosen for some chemicals, as a proxy for European production, considering that these processes are based on similar technologies worldwide. LCIA is performed by means of the LCA software OpenLCA 1.3 (www.openlca.org) and Ecoinvent v 2.2 using the CML 2001 and the CED (Cumulative Energy Demand) methods. The first one, developed by the Centre of Environmental Science at Leiden University in the Netherlands , is a LCIA mid-point methodology providing characterization and normalization factors updated on a regular basis, which can be profitably used to quantify environmental impacts for the impact categories chosen in this study: Abiotic Depletion Potential (ADP, in kg Sb eq), Acidification Potential (AP, in kg $SO_2$ eq), Eutrophication Potential (EP, in kg $PO_4^3$eq), Global Warming Potential (GWP, in kg $CO_2$ eq), Human Toxicity Potential (HTP, in kg 1,4-DB eq), Photochemical Oxidation Potential (POP, in kg $C_2H_4$). All the analyzed categories are referred to the CML 2001 baseline version. The second method (CED) is applied to investigate the use of non-renewable (fossil, nuclear, biomass from primary forests) and renewable (biomass from agriculture, wind, solar, geothermal, water) sources involved in the production system, to be interpreted as patterns of energy resource investment and depletion.

### *Results and Discussion*

In order to assess the suitability of biodiesel from WCO as an alternative fuel, a comparison among biodiesel from WCO, biodiesel from rapeseed and fossil diesel was accomplished. All the inputs and outputs were referred to the production of 1 kg of biodiesel from rapeseed and diesel from fossil resources, appropriately adjusted from the Ecoinvent database; the processes taken into account were "*diesel, at refinery*" and "*rape methyl ester, at esterification plant*". In order to make the processes more fit to the Italian context, in both cases the Italian electricity mix was included. The impacts calculated throughout the CML 2001 and the CED methods for the different type of diesel are listed below. Table 3.2 and 3.3 show the environmental impact associated to the different production processes. In each impact category, the total impacts associated with biodiesel production from WCO are much lower than those associated with biodiesel production from rapeseed and fossil diesel. Furthermore, biodiesel from rapeseed shows the highest impact in Global Warming category in comparison to the other diesel production processes. Global Warming impacts are mainly generated by the agricultural phase (fertilizers, pesticides, machinery, among others) requiring a large amount of fossil resources, whilst the impacts generated by the industrial steps are much lower (Gasol et al., 2007; Bozell and Petersen, 2010). This evidence, confirmed by previous studies (Fahd et al., 2012; Fiorentino et al., 2014), underlines that the use of dedicated biomass is not feasible for energy production only (biodiesel and heat).

**Table 3.2**. CML 2001 characterized impacts calculated for the comparison among biodiesel from WCO, rapeseed and fossil diesel.

| Impact Category | Unit | Biodiesel from WCO | Biodiesel from rapeseed | Fossil diesel |
|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 4.66E-03 | 1.11E-02 | 2.37E-02 |
| Acidification | kg $SO_2$ eq | 1.19E-03 | 1.70E-02 | 5.40E-03 |
| Eutrophication | kg $PO_4^{3-}$eq | 1.74E-04 | 5.47E-03 | 2.76 -04 |
| Global warming | kg $CO_2$ eq | 0.32 | 2.62 | 0.49 |
| Human toxicity | kg 1,4-DB eq | 9.66E-02 | 1.12 | 0.25 |
| Photochemical oxidation | kg $C_2H_4$ | 7.58E-05 | 1.18E-03 | 3.39E-04 |

Concerning the CED method, Table 3.3 shows that biodiesel production from WCO and fossil diesel are mainly relying on non-renewable fossil sources, accounting for 98% and 99% of the total energy demand, respectively. Although the biodiesel production from rapeseed is only partially dependent on non-renewable energy sources (34%), in absolute values it represents the most demanding diesel production process, showing the highest energy consumption and the highest values in almost all impact categories. Biodiesel production from WCO shows the lowest energy demand and it requires 10.31 MJ/kg of energy, of which 9.59 MJ/kg from fossil fuels, 0.56 MJ/kg from nuclear (indirectly, through imports from France) and only a minor contribution (0.16 MJ/kg) from renewables, 81% of which from Renewable, hydro. This positive balance suggests that the biodiesel production from WCO is also feasible from an energy perspective.

**Table 3.3**. CED impacts calculated for the comparison among biodiesel from WCO, rapeseed and fossil diesel.

| Impact Category | Unit | Biodiesel from WCO | Biodiesel from rapeseed | Fossil diesel |
|---|---|---|---|---|
| Non-renewable, fossil | MJ | 9.59 | 22.5 | 53.4 |
| Non-renewable, nuclear | MJ | 0.56 | 2.78 | 0.60 |
| Non-renewable, biomass | MJ | 1.44E-04 | 1.23E-03 | 6.33E-05 |
| Renewable, biomass | MJ | 2.32E-02 | 47.6 | 2.21E-02 |
| Renewable, wind, solar, geothermal | MJ | 7.80E-03 | 3.26E-02 | 1.13E-02 |
| Renewable, hydro | MJ | 0.13 | 0.47 | 7.07E-02 |

In order to highlight the contribution of each phase of the system, the environmental impacts of biodiesel production from WCO on CML 2001 and CED categories were explored step by step. The results (not shown here) highlights that the trans-esterification is the stage with greater impact in all impact categories with contributions between 48% and 68% (assuming a total impact equalling to 100%) and the most impacted categories are Abiotic Depletion and Global Warming. A deeper analysis of the tras-esterification step (not shown here) underlines that the use of methanol itself contributes to Abiotic Depletion by 70%, to Global Warming by 43% and to Non-renewable, fossil by 71%, whereas a minor contribution comes from the other inputs. This is due to the fact that the methanol production process (steam reforming) is strictly dependent from natural gas, strongly impacting respectively on Abiotic Depletion, Global Warming and Non-renewable-fossil categories.

*Conclusions*

The LCA methodology applied in this study helped identify the hotspots throughout the entire biodiesel from WCO production chain, pointing out the trans-esterification phase to be responsible for the largest part of the emissions. Although it is unlikely that biofuel production would be a viable alternative to petroleum fuels, the use of biodiesel from WCO shows promising potential: firstly, it can contribute to the reduction of environmental impacts of WCO disposal; secondly, it reduces the economic load related to the operation problems in municipal sewage treatment plants and, thirdly, it contributes a small but non-negligible fraction of renewable energy to society.

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# Chapter 3.b Power generation from animal by-products

## Introduction

The increasing demand for fossil fuel gives rise to environmental concerns such as larger $CO_2$ and greenhouse gas (GHG) emissions and global warming. The world energy consumption doubled between 1971 and 2001 and the world energy demand is expected to increase by 53% within the year 2030 (Talebian-Kiakalaieh et al., 2013). Waste generation applies pressure on both the environment and the human health, thus calling for improved waste management strategies to replace the present polluting methods. For instance, landfilling is one of the most commonly used waste disposal method, and accounts for approximately 67% of the total collected MSW worldwide (United Nations Statistics Division, 2011) (31% in the only European Community (Eurostat, 2015)) with heavy environmental consequences due to leachate contamination of underground water as well as methane release to the atmosphere; incineration, most often considered as another mainstream technology, has faced a rapid development in recent years, in spite of the fact that toxic substances such as heavy metals and dioxin released during combustion may cause negative effects to the environment and human health (Dong et al., 2014; Palmiotto et al., 2014), entailing heavy costs for management (Martinez-Sanchez et al., 2015) and being a cause of degradation for the standard of living of populations in urbanized environments. The energy sector is the largest contributor to GHG emissions (Eurostat, 2012), and for this reason, strategies to reduce the emissions from this sector are a key point of climate change mitigation strategies (Evangelisti et al., 2015). Waste contains biogenic materials, such as paper, card and food waste, that can be potentially converted into energy. The implementation of waste-to-energy (WTE) supply chains was suggested as a suitable method for energy production from waste, in order to address two of the main waste management environmental issues (limited landfilling sites and leachate). The WTE supply chain, in its CHP (Combined Heat & Power) version, if properly managed provides a method for simultaneously addressing energy demand, waste management and GHG emissions within a circular economy perspective (CES) (Pan et al., 2015). The recycling of materials, and thus the minimization of waste to be disposed of, is a basic concept which must be implemented in order to meet the sustainable development goals in both industrialized and developing countries. The EU Directives on waste management prescribe prevention, reuse and recycling as the very first alternatives, indicating the energy recovery option only for smaller amounts for which the previous alternatives are not easily feasible or fail. This seems to be the case of fat fractions of slaughterhouse residues, after other uses have been explored. The generation of agro-industrial waste has been rising to such alarming levels that the public has become aware of the problems caused by inaccurate management. Nowadays the generation of waste biomass is so abundant and so centralized that there is insufficient capacity for its natural degradation, and various treatment techniques have to be applied. Animal slaughterhouse waste is also city related, in that the demand for meat-based diet is growing in cities and is not expected to decrease in the short run. Slaughterhouses represent one of the most important sectors of the meat industry (Marcos et al., 2010). Non-edible feedstocks, such as animal fat waste (AFW), have recently increased in popularity as alternatives to vegetable oils in the production of biodiesel (Adewale et al., 2015; Alptekin et al., 2015; Behçet et al., 2015; Chakraborty et al., 2014). Animal by-products are defined by European Directive 2002/1774/EC as entire bodies, or parts of animals or products of animals, not intended for human consumption. Animal fats are primarily derived as by-products of meat animal processing facilities and of the rendering process. A large percentage of livestock live weight (an amount of about 48% by mass) consists of byproducts (i.e. fat and meal) (Haines, 2004) which show an energy content not far from diesel fuel (animal fat: 3.98E+04 J/g average, animal meal: 1.85E+04 J/g average) (Ariyaratne et al., 2010; Kumar et al., 2006). The present work explores, by means of the LCA and emergy method, the environmental feasibility of processing slaughterhouse animal waste electricity as a case study in Campania Region (Italy), addressing simultaneously the European energy Directive 2009/28/EC and waste directives Directive 2008/98/EC.

**Materials and Methods**

The methodological framework used in this paper is the LCA, as defined by ISO standards and ILCD Handbook guidelines (ISO 14040:2006; ISO 14044:2006; JRC 2010), and emergy assessment. The full rendering process and electricity generation process has been assessed under different perspectives, in order to understand how they affect the final results. Regarding the LCA method, animal by-products stream has been accounted alternatively as a waste stream and as a product stream, also comparing the electric energy obtained to the one coming from the Italian grid. Different approaches has been considered also to allocate burdens at the different products generated by the rendering process. Within the emergy method, animal by-products flow and meat flow, coming from the livestock phase, will be allocated alternatively as split flows and co-products. Across these two cases, other two sub-cases are investigated, considering alternatively the animal fat and the animal meal obtained after the rendering process as split and co-products flows. The environmental performances of the electricity produced will be compared to those of the Italian mix of electric energy and to those of electricity obtained by only using fossil fuel and photovoltaic. The entire process, operated by Proteg S.P.A., a company located in the industrial area of the municipality of Caivano (Italy), can be divided into two sub-processes: 1) Rendering process of the organic material, yielding meal and fat fractions; 2) Generation of electric energy from combustion of animal fat (Figure 3.2).

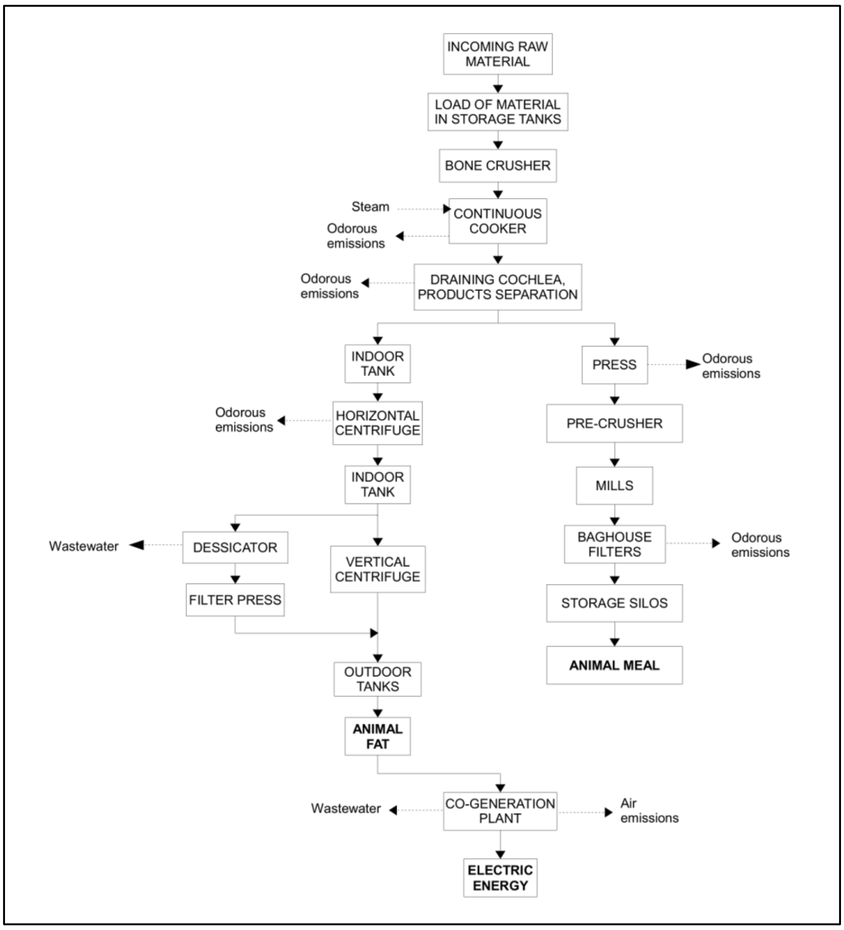



**Figure 3.2.** Rendering process and electricity generation schematic diagram.

The industrial plant is capable of producing average 5.1 MW of electric energy using animal by-products properly processed. The system under examination consists of three stages: 1) collection of AFWs, 2) rendering process in order to obtain animal meal and animal fat, and 3) AFW conversion into electricity through refining and combustion of about half of the animal fat produced in a marine-derived engine. The animal meal and the remaining part of the fat (around 50% by mass) are sold to the market. The significant difference between LCA and emergy assessment is the definition of system boundaries, that is strictly connected to the perspective used to analyze a given system: while in LCA the boundaries generally are the temporal and spatial ones of the life cycle of a given process, in emergy assessment the system is considered as a part of a greater natural system, including all direct and indirect flows needed, on a larger spatial and temporal frame.

**LCA**

Goal and scope

The main purpose of this work is to analyze the generation of electric energy from AFW, coming from the rendering process of animal by-products, comparing it to the electricity production by conventional routes. The Functional Unit (FU) referred to in this study is 1 MWh of electric energy produced. All input flows and environmental burdens are allocated to the meal and fat exiting the first phase as co-products; then, the fraction of inflows and outflows allocated to fat is assigned to the electricity generated in the second phase. A ‘gate to gate’ approach is used, since the system boundary is considered coincident with the physical boundaries of the plant. The analyzed context can thus be identified as a micro-level decision support (so called situation A in ILCD) and an attributional LCI modeling framework is therefore applied. Three different has been considered:

- Case 1: animal by-products are considered waste, with a ‘zero burden’ approach; a mass allocation between meal and fat is performed (Table 3.4);
- Case 2: animal by-products are considered a product, bringing all the impacts related to the livestock phase, and meal and fat are allocated by mass;
- Case 3: animal by-products are considered waste, with a ‘zero burden’ approach; an energy allocation, based on the energetic content, between meal and fat is performed (Table 3.4);

**Table 3.4**. Mass and energy allocation between animal fat and animal meal produced by the rendering process.

| Input | Quantity | Unit | Mass allocation (%) | Energy allocation (%) |
|---|---|---|---|---|
| Treated organic waste | 1.80E+03 | kg/MWh | | |
| **Output** | | | | |
| Fat | 4.33E+02 | kg/MWh | 47 | 65 |
| Meal | 4.97E+02 | kg/MWh | 53 | 35 |
| Wastewater and other residues | 8.70E+02 | kg/MWh | | |

Life Cycle Inventory

Local data were collected for each of the above-mentioned phases: all different materials (e.g. concrete, steel, glass), machinery, as well as the energy consumption for buildings construction, and plant operation. The construction and delivery of the major components of the power plant were also included. Table 3.5 presents a simplified inventory (LCI), organized according the two steps: (a) inventory of the rendering phase (Table 3.5a) and (b) inventory of electricity production (Table 3.5b). All the flows in Table 3.5 are referred to 1 MWh of electric energy produced (functional unit). Primary data, e.g. specific information about input flows to the process, recovered materials and emissions were made available by Proteg S.P.A. When direct measurements were not available, estimations were made by experts in both Company and research team, and their consistency was verified in literature. Background data over the supply chain of energy and materials were derived from the Ecoinvent v3.0 database. In particular, a comparative LCIA between electricity production from AFW and Italian electricity mix has been carried out: key data for the quantification of inputs and outputs of the Italian production mix of medium voltage electricity were derived from Ecoinvent database.

**Table 3.5a*** . Rendering process inventory.

| Input | Unit | Amount/MWh |
|---|---|---|
| Animal by-products | kg | 1.80E+03 |
| Electricity from animal fat feedback | kWh | 1.41E+02 |
| Underground water | kg | 1.16E+03 |
| Methane | $m^3$ | 1.17E+02 |
| Transportation | t*km | 2.07E+02 |
| **Output** | **Unit** | **Amount/MWh** |
| Animal fat | kg | 4.33E+02 |
| Animal meal | kg | 4.97E+02 |
| Particulate | kg | 7.16E-02 |
| $NO_x$ | kg | 6.83E-01 |
| $SO_x$ | kg | 4.68E-01 |
| CO | kg | 2.68E-01 |
| TOC | kg | 1.16E-01 |
| VOC | kg | 4.07E-01 |
| $NH_3$ | kg | 9.72E-02 |

**Table 3.5b*** . Electricity generation process inventory.

| Input | Unit | Amount/MWh |
|---|---|---|
| Animal fat | kg | 2.32E+02 |
| Diesel fuel | kg | 2.91E-01 |
| Lubricating oil | kg | 2.14E-01 |
| Urea | kg | 1.33E+01 |
| **Output** | **Unit** | **Amount/MWh** |
| Electricity from animal fat | MWh | 1 |
| Hot water | $m^3$ | 7.72E+00 |
| CO | kg | 3.98E-01 |
| $O_2$ | kg | 5.17E+02 |
| $NO_2$ | kg | 9.33E-01 |
| Particulate | kg | 2.39E-01 |

**The inventory only includes the main flows. Capital goods and machinery are not included for lack of space, but where accounted for in the results.*

Life Cycle Impact Assessment

LCIA was performed by means of the LCA software SimaPro 8.0.5.13. The impact assessment was performed by means of one of the most recent and up-to-date LCA methods, the ReCiPe method (Goedkoop et al., 2009). In particular, ReCiPe Midpoint (H) v.1.12 (http://www.lcia-recipe.net/) was chosen. The ReCiPe method provides characterization factors to quantify the contribution of processes to each impact category and normalization factors to allow a comparison across categories (Europe ReCiPe Midpoint (H), 2000, revised 2010). In this study, the following categories are explored: Global Warming Potential (GWP, in kg $CO_2$ eq), Human Toxicity Potential (HTP, in kg 1,4-DB eq), Fossil Depletion Potential (FDP, in kg oil eq), Metal Depletion Potential (MDP, in kg Fe eq), Water Depletion Potential (WDP, in $m^3$), Freshwater Eutrophication Potential (FEP, in kg P eq), Terrestrial Acidification Potential (TAP, in kg $SO_2$ eq), Terrestrial Ecotoxicity Potential (TEP, kg 1,4-DB eq), Photochemical Oxidant Formation Potential (POFP, in kg NMVOC).

**Emergy analysis**

It is clear that the LCA impact assessment method has a 'consumer-side' perspective, while emergy assessment has a 'donor-side' perspective (Raugei et al., 2014). In this paper, boundaries have been drawn around the process, including slaughterhouse producing meat and animal by-products. The process has been divided into two sub–processes: 1) rendering process, to separate animal meal from animal fat; 2) use of part of the fat as fuel for the co-generation plant. In order to combine LCA and emergy accounting, two different assumptions about the animal by-products entering the process have been made. Keeping in mind the emergy algebra rules (Odum, 1996), two different cases have been distinguished:

- Case 1: animal by-products and meat flows in output from the slaughtering phase are considered as split, with a proportional emergy content based on economic value. An emergy equal to zero is then assigned to the animal by-products entering the process. The choice is valid because the material is collected by Proteg S.P.A. without any cost (Figure 3.3);
- Case 2: animal by-products and meat flows are considered as co-products of the slaughtering process (because meat cannot be obtained without producing also by-products), so the entire emergy content of the process is assigned to both of them.

Within the two cases listed above, two additional cases have been considered, making another assumption at the end of the rendering process:

- Case A: animal meal and animal fat flows at the end of the rendering process are considered as split, and the emergy content is assignment with regards on the energetic content (Figure 3.3);
- Case B: animal meal and animal fat flows are considered as co-products, then both of them carry the entire emergy from the rendering process.

All data used for the inventory phase come from the investigated company and from literature and/or specialized archives or websites (i.e. the data regarding solar radiation, wind, rain, etc.). All flows have been properly allocated to the chosen functional unit of 1 MWh of electric energy produced, and all the UEVs are related to the Brown & Ulgiati (2010) baseline.

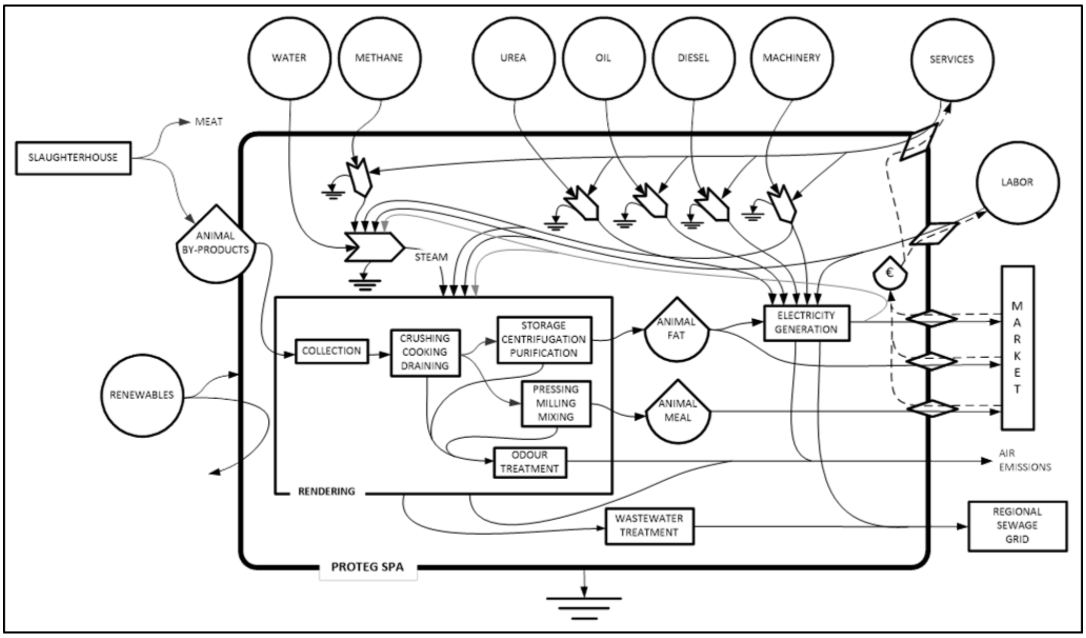



**Figure 3.3.** System diagram of CASE 1-A.

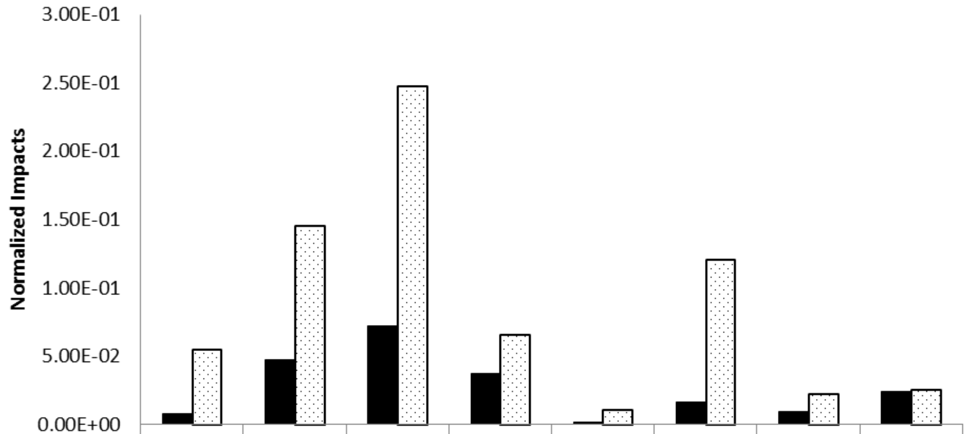
## Results and Discussion

LCA characterized impacts of CASE 1 electricity production from AFW are shown in Table 3.6. In order to gain an understanding of the suitability of such electricity generation process, a comparison with the impacts of the Italian electric mix was also accomplished, with reference to the production of 1 MWh of electricity. In each impact category, the total impact associated with electricity production from AFW is much lower than those associated with the Italian mix (MIX ITA), being the latter mainly derived from fossil fuels (with a large fraction of natural gas). In some impact categories – i.e. global warming, metal and water depletion the impacts generated in CASE 1 process are around one order of magnitude smaller than MIX ITA.

**Table 3.6**. ReCiPe Midpoint (H) characterized impacts calculated for the generation of 1 MWh of electric energy for CASE 1 and MIX ITA.

| Impact category | Unit | CASE 1 | MIX ITA |
|---|---|---|---|
| GWP | kg $CO_2$ eq | 8.47E+01 | 6.08E+02 |
| HTP | kg 1,4-DB eq | 2.96E+01 | 9.13E+01 |
| FEP | kg P eq | 1.73E-02 | 1.02E-01 |
| TAP | kg $SO_2$ eq | 1.27E+00 | 2.24E+00 |
| TEP | kg 1,4-DB eq | 1.26E-02 | 8.44E-02 |
| FDP | kg oil eq | 2.53E+01 | 1.88E+02 |
| MDP | kg Fe eq | 6.47E+00 | 1.59E+01 |
| POFP | kg NMVOC | 1.35E+00 | 1.42E+00 |
| WDP | $m^3$ | 1.15E+02 | 3.12E+03 |

Figure 3 shows the normalized impacts of the same processes. The most affected categories are human toxicity (4.70E-2) and freshwater eutrophication (7.24E-2). Water depletion category is not detectable at all, due to the normalization factor equal to zero, and it is not shown in the Figure 3.4.




| | GWP | HTP | FEP | TAP | TEP | FDP | MDP | POFP |
|---|---|---|---|---|---|---|---|---|
| ■ CASE 1 | 7.56E-03 | 4.70E-02 | 7.24E-02 | 3.70E-02 | 1.52E-03 | 1.63E-02 | 9.05E-03 | 2.37E-02 |
| ☐ MIX ITA | 5.43E-02 | 1.45E-01 | 2.47E-01 | 6.53E-02 | 1.02E-02 | 1.21E-01 | 2.22E-02 | 2.50E-02 |

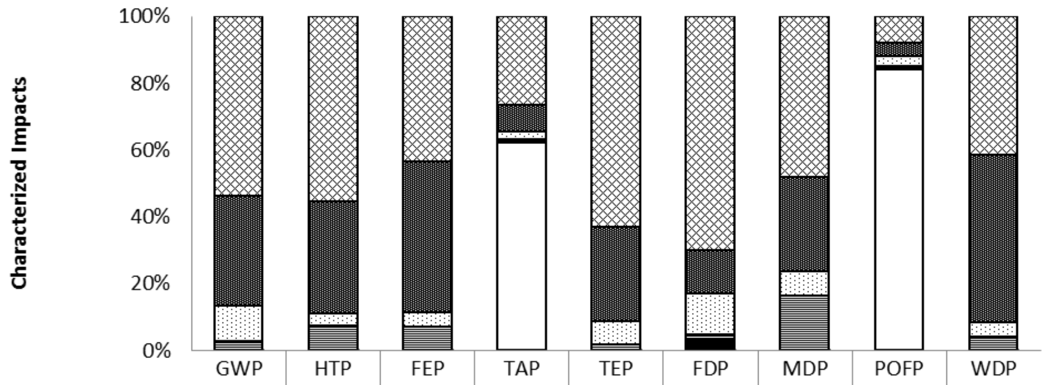
**Figure 3.4**. ReCiPe Midpoint H normalized impacts for CASE 1 and MIX ITA. Units on vertical axis are not shown, since values are unit-less ratios of actual burdens to reference burdens for standardization.

Table 3.7 compares the characterized results associated with the 3 cases considered. While CASE 3 shows only slightly larger impacts than CASE 1, CASE 2 shows much greater impacts in every category. For the categories HTP, FDP, POFP and WDP, the impact generated by CASE 2 are one order of magnitude greater than CASE 1, while for GWP, FEP, TAP, TEP and MDP the impacts generated are about two orders of magnitude greater.

**Table 3.7.** ReCiPe Midpoint (H) characterized impacts calculated for the generation of 1 MWh of electric energy for CASE 1, CASE 2 and CASE 3.

| Impact category | Unit | CASE 1 | CASE 2 | CASE 3 |
|---|---|---|---|---|
| GWP | kg $CO_2$ eq | 8.47E+01 | 6.15E+03 | 9.98E+01 |
| HTP | kg 1,4-DB eq | 2.96E+01 | 4.42E+02 | 3.42E+01 |
| FEP | kg P eq | 1.73E-02 | 1.96E+00 | 2.09E-02 |
| TAP | kg $SO_2$ eq | 1.27E+00 | 1.49E+02 | 1.43E+00 |
| TEP | kg 1,4-DB eq | 1.26E-02 | 4.90E+00 | 1.44E-02 |
| FDP | kg oil eq | 2.53E+01 | 2.88E+02 | 2.80E+01 |
| MDP | kg Fe eq | 6.47E+00 | 1.10E+02 | 7.60E+00 |
| POFP | kg NMVOC | 1.35E+00 | 1.01E+01 | 1.46E+00 |
| WDP | $m^3$ | 1.15E+02 | 2.15E+03 | 1.44E+02 |

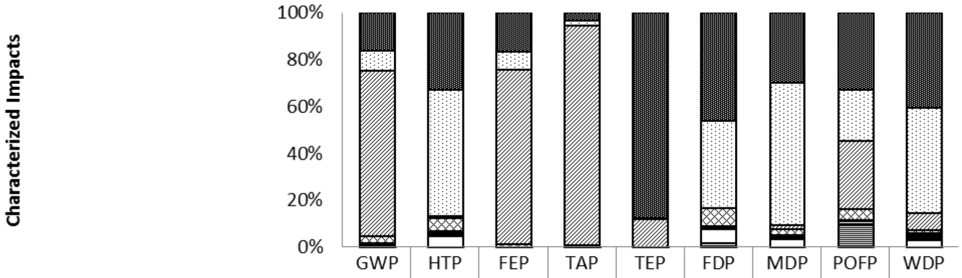
Figure 3.5 displays the percentage contribution of each process step to selected impact categories in CASE 1. Such breakdown of impacts confirms that the highest impacts in all categories come from the operation step, while construction (e.g. machinery and capital goods) plays a minor role, except for metal depletion (16% of total impact). The use of urea itself (for the control of $NO_x$ emissions in the co-generation plant) results to be the largest share of the global warming potential category (54%) and of the fossil depletion (70%), whereas only minor contributions come from the other input flows. Likewise, the contribution of urea is also high in the terrestrial acidification, freshwater eutrophication, human toxicity, metal and water depletion categories. Beyond urea, the second main contribution to environmental burdens comes from the use of methane (for the generation of steam) in global warming, human toxicity, freshwater eutrophication and water depletion, ranging from 28% to 50%. Local emissions provide a major contribution to terrestrial acidification and photochemical oxidant formation, with values of 62% and 84%, respectively.




| | GWP | HTP | FEP | TAP | TEP | FDP | MDP | POFP | WDP |
|---|---|---|---|---|---|---|---|---|---|
| Urea | 54% | 56% | 43% | 26% | 63% | 70% | 48% | 8% | 42% |
| Methane | 33% | 34% | 45% | 8% | 28% | 13% | 28% | 4% | 50% |
| Transportation | 11% | 4% | 4% | 2% | 7% | 12% | 7% | 3% | 4% |
| Machinery | 2% | 7% | 7% | 1% | 2% | 2% | 16% | 1% | 4% |
| Diesel+Oil | 0% | 0% | 0% | 0% | 0% | 3% | 0% | 0% | 1% |
| Local Emissions | 0% | 0% | 0% | 62% | 0% | 0% | 0% | 84% | 0% |

**Figure 3.5**. Percent contributions to characterized impacts from different phases of CASE 1.

Figure 3.6 clarifies why this worse performance of CASE 2 occurs. Figure shows the percentage contribution of each process to the characterized impacts in CASE 2 assumption. In every impact category, the contribution is almost entirely attributable to the livestock phase, which provides a contribution greater than 90% in almost all categories, with exception of POFP. In detail, the major contributions come the feeding related processes ranging from 3% (TAP) to 88% (TEP); the shed and crops processes, ranging from 1% (TEP), to 61% (MDP). Transport has a lower impact contribution, with a peak of 8% in FDP. Local emissions show a notable contribution of 70% in GWP, 75% in FEP, 94% in TAP and 29% in POFP. Impacts contributions coming from the investigated process phase are almost always negligible. A non-negligible contribution from urea is observed in HTP (4%), FDP (6%), MDP (3%), GWP (1%) and WDP (1%), while methane contributes to HTP (2%), FDP (1%), MDP (2%), POFP (1) and WDP (2%). Local emissions from the investigated process show a valuable contributions (10%) to POFP.




| | GWP | HTP | FEP | TAP | TEP | FDP | MDP | POFP | WDP |
|---|---|---|---|---|---|---|---|---|---|
| Feed (Livestock) | 16% | 33% | 17% | 3% | 88% | 46% | 30% | 33% | 41% |
| Shed+Crops (Livestock) | 9% | 54% | 7% | 2% | 1% | 37% | 61% | 22% | 45% |
| Local Emissions + Others (Livestock) | 70% | 1% | 75% | 94% | 11% | 0% | 2% | 29% | 7% |
| Transportation (Livestock) | 3% | 6% | 0% | 0% | 0% | 8% | 3% | 5% | 2% |
| Methane | 0% | 2% | 0% | 0% | 0% | 1% | 2% | 1% | 3% |
| Urea | 1% | 4% | 0% | 0% | 0% | 6% | 3% | 1% | 2% |
| Local Emissions + Others (Electricity Production) | 0% | 1% | 0% | 0% | 0% | 2% | 1% | 10% | 1% |

**Figure 3.6.** Contributions to characterized impacts from different phases of CASE 2 (contributions less than 1% from the livestock phase are included in 'Local emissions + Others(Livestock)', while contributions less than 1% from the electricity production phase are labeled as 'Local emissions +Others (Electricity production)').

In order to assess the uncertainty caused by variability in input and output data, a Monte Carlo analysis has been performed. Prior to performing the Monte Carlo analysis, a pedigree matrix was created. Results, for the selected impact categories, are summarized in Table 3.8.

**Table 3.8**. Results of Monte Carlo applied to the production of 1MWh of electric energy in CASE 1.

| Impact category | Unit | Mean | Median | σ | $c_v$ | SEM |
|---|---|---|---|---|---|---|
| GWP | kg $CO_2$ eq | 84.51 | 83.38 | 8.89 | 10.52% | 0.28 |
| HTP | kg 1,4-DB eq | 88.02 | 81.68 | 1377.24 | 1564.68% | 43.55 |
| FEP | kg P eq | 0.02 | 0.01 | 0.01 | 53.67% | 2.86E-04 |
| TAP | kg $SO_2$ eq | 1.27 | 1.26 | 0.07 | 5.35% | 2.15E-03 |
| TEP | kg 1,4-DB eq | 0.01 | 0.01 | 0.04 | 251.48% | 1.12E-03 |
| FDP | kg oil eq | 25.27 | 24.71 | 3.95 | 15.62% | 0.12 |
| MDP | kg Fe eq | 6.37 | 5.72 | 2.69 | 42.27% | 0.09 |
| POFP | kg NMVOC | 1.35 | 1.34 | 0.03 | 2.58% | 1.10E-03 |
| WDP | $m^3$ | 114.25 | 111.23 | 16.91 | 14.80% | 0.53 |

**σ** = Standard deviation **$c_v$** = Coefficient of variation **SEM** = Standard error of mean

Table 3.8 confirms the reliability of the results achieved in this paper, even with the presence of a few large values of σ and cv in some impact categories (i.e. HTP and TEP).

From an emergy point of view, Tables 3.9a and 3.9b summarize all the relevant input and output flows of respectively the rendering and the electricity generation processes, from the CASE 1-A approach. The input flow of electric energy feedback in Table 3.9a is equal to zero because the output flow of electricity produced in Table 3.9b is relative to the net production.

**Table 3.9a.** Emergy accounting – Rendering (CASE 1 – A).

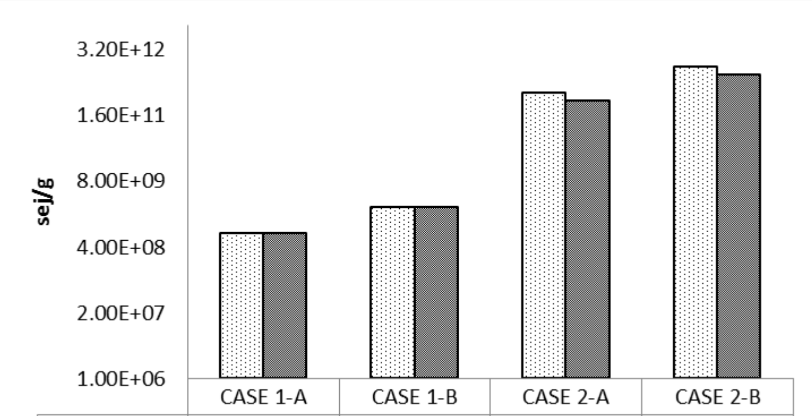
| # | Item | Unit | Input | UEV (sej/unit) | Emergy Flow (sej/MWh) | Ref. |
|---|---|---|---|---|---|---|
| | ***Renewable Input*** | | | | | |
| 1 | Sun | J | 5.91E+06 | 1.00E+00 | 5.91E+06 | Def. |
| 2 | Rain | J | 3.66E+05 | 6.36E+03 | 2.33E+09 | After Odum et al. 2000 |
| 3 | Wind | J | 1.86E+00 | 2.42E+03 | 4.48E+03 | After Odum 1996 |
| | ***Imported Renewable Input*** | | | | | |
| 4 | Renewable fraction of Labor | people/yr | 2.07E-05 | 3.46E+16 | 7.15E+11 | After Cialani et al. 2005 |
| 5 | Renewable fraction of Services | € | 2.85E-01 | 9.60E+11 | 2.73E+11 | Buonocore et al. 2015 |
| 6 | Renewable fraction of Electricity Feedback | J | 0.00E+00 | | | |
| | ***Non-Renewable Input*** | | | | | |
| 7 | Underground water | J | 5.73E+03 | 2.93E+06 | 1.68E+10 | After Odum 1996 |
| | ***Purchased Input*** | | | | | |
| 8 | Cat. 3 Material | g | 1.80E+06 | 0.00E+00 | 0.00E+00 | Assumed from economical allocation |
| 9 | Methane | J | 4.67E+09 | 1.70E+05 | 7.94E+14 | Brown et al. 2011 |
| 10 | Diesel for transportation | J | 1.30E+09 | 1.81E+05 | 2.36E+14 | Brown et al. 2011 |
| 11 | Non-Renewable fraction of Electricity Feedback | J | 0.00E+00 | | | |
| | *Machinery* | | | | | |
| 12 | Steel | g | 1.05E+03 | 3.03E+09 | 3.17E+12 | After Bargigli & Ulgiati 2003 |
| 13 | Aluminum | g | 1.41E+01 | 2.01E+10 | 2.84E+11 | After Buranakarn 1998 |
| 14 | Plastics & Rubbers | g | 8.41E+01 | 3.54E+09 | 2.98E+11 | After Ghisellini et al. 2014 |
| 15 | Copper | g | 2.43E+00 | 3.22E+09 | 7.84E+09 | After Lapp 1991 |
| 16 | Cast Iron | g | 4.56E+00 | 2.40E+09 | 1.09E+10 | After Bargigli & Ulgiati 2003 |
| 17 | Lead | g | 2.72E-01 | 4.61E+11 | 1.25E+11 | After Cohen et al. 2007 |
| 18 | Iron | g | 7.10E+00 | 3.03E+09 | 2.15E+10 | After Bargigli & Ulgiati 2003 |
| 19 | Glass | g | 2.07E-01 | 3.48E+09 | 7.21E+08 | After Buranakarn 1998 |
| 20 | Polypropylene | ton | 3.73E-06 | 2.07E+15 | 7.73E+09 | After Mu et al. 2012 |
| 21 | Silicon Carbide | g | 1.49E+01 | 2.94E+09 | 4.38E+10 | After Ganeshan & Tilley 2005 |
| 22 | Polyethylene | g | 2.54E+01 | 8.50E+09 | 2.16E+11 | After Pulselli et al. 2007 |
| 23 | Concrete | g | 4.34E+03 | 2.48E+09 | 1.07E+13 | After Buranakarn 1998 |
| 24 | Limestone | kg | 3.88E-02 | 2.72E+12 | 1.05E+11 | After Odum 1996 |
| 25 | Fiber Glass | g | 3.54E+00 | 9.45E+09 | 3.35E+10 | After Buranakarn 1998 |
| 26 | Rock Woll | g | 1.58E+00 | 2.96E+09 | 4.68E+09 | After Björklund et al. 2001 |
| 27 | Bitumen | J | 3.54E+04 | 1.73E+05 | 6.13E+09 | Brown et al. 2011 |
| 28 | Non-Renewable fraction of Labour | people/yr | 6.69E-04 | 3.46E+16 | 2.31E+13 | After Cialani et al. 2005 |
| 29 | Non-Renewable fraction of Services | € | 9.21E+00 | 9.60E+11 | 8.84E+12 | Buonocore et al. 2015 |
| | ***Total*** | | | | | |
| 30 | Animal Fat (with L&S) | g | 4.33E+05 | 7.56E+08 | 7.03E+14 | This Work |
| 31 | Animal Meal (with L&S) | g | 4.97E+05 | 4.03E+08 | 3.75E+14 | This Work |
| 32 | Animal Fat (without L&S) | g | 4.33E+05 | 7.33E+08 | 6.81E+14 | This Work |
| 33 | Animal Meal (without L&S) | g | 4.97E+05 | 3.91E+08 | 3.64E+14 | This Work |

Figures 3.7, 3.8 and 3.9 summarize the UEVs for all four cases, with and without Labor and Services (L&S), of respectively the animal fat, the animal meal and the electric energy produced. Regarding the animal fat, the UEVs calculated including L&S are only slightly larger than the ones calculated without L&S: the UEV without L&S are 7.33E+08 sej/g for CASE 1-A, 2.41E+09 sej/g for CASE 1-B, 3.07E+11 sej/g for CASE 2-A and 1.01E+12 sej/g for CASE 2-B, while including L&S, the UEVs are respectively equal to 7.56E+08 sej/g, 2.49E+09 sej/g, 4.41E+11 sej/g and 1.45e+12 sej/g. A similar situation can be seen for the UEVs relative to the animal meal production: for CASE 1-A the UEVs are 3.91E+08 sej/g without L&S and 4.03E+08 with L&S; for CASE 1-B, 2.10E+09 sej/g without L&S and 2.17E+09 sej/g with L&S;

for CASE 2-A, 1.64E+11 without L&S and 1.70E+11 sej/g with L&S; for CASE 2-B; 8.82E+11 without L&S and 1.27E+12 with L&S. Looking at the values calculated for the electric energy generated, without L&S, the UEV of CASE 1-A is equal to 1.13E+05 sej/J, the UEV of CASE 1-B is 2.39E+05 sej/J, the UEV of CASE 2-A is 2.31E+07 sej/J and the UEV of CASE 2-B is 7.60E+07 sej/J. Things are different including L&S: all UEVs, except the one of CASE 2-A, are greater of one order of magnitude than without L&S, showing values of (in the same order as above) 3.82E+06 sej/J, 3.95E+06 sej/J, 3.69E+07 sej/J and 1.13E+08 sej/J.

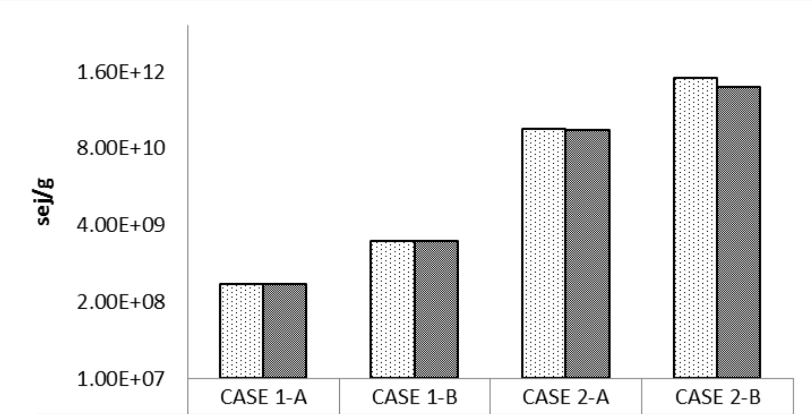
**Table 3.9b.** Emergy accounting – Electric energy generation (CASE 1 – A).

| # | Item | Unit | Input | UEV (seJ/unit) | Emergy Flow (seJ/MWh) | Ref. |
|---|---|---|---|---|---|---|
| | ***Renewable Input*** | | | | | |
| 1 | Sun | J | 4.79E+05 | 1.00E+00 | 4.79E+05 | Def. |
| 2 | Rain | J | 2.97E+04 | 6.36E+03 | 1.89E+08 | After Odum et al. 2000 |
| 3 | Wind | J | 3.51E-01 | 2.42E+03 | 8.48E+02 | After Odum 1996 |
| 4 | Renewable fraction of Animal Fat (with L&S) | g | 2.14E+02 | 7.56E+08 | 1.62E+11 | This Work |
| 5 | Renewable fraction of Animal Fat (without L&S) | g | 5.18E-01 | 7.33E+08 | 3.80E+08 | This Work |
| | ***Imported Renewable Input*** | | | | | |
| 6 | Renewable fraction of Services | € | 3.57E+02 | 9.60E+11 | 3.43E+14 | Buonocore et al. 2015 |
| 7 | Renewable fraction of Labour | people/yr | 2.07E-05 | 3.46E+16 | 7.15E+11 | After Cialani et al. 2005 |
| | ***Non-Renewable Input*** | | | | | |
| 8 | Non-Renewable fraction of Animal Fat (with L&S) | g | 2.32E+05 | 7.56E+08 | 1.75E+14 | This Work |
| 9 | Non-Renewable fraction of Animal Fat (without L&S) | g | 2.32E+05 | 7.33E+08 | 1.70E+14 | This Work |
| | ***Purchased Input*** | | | | | |
| 10 | Diesel | J | 1.19E+07 | 1.81E+05 | 2.16E+12 | Brown et al. 2011 |
| 11 | Lubricating oil | J | 9.00E+06 | 1.81E+05 | 1.63E+12 | Brown et al. 2011 |
| 12 | Urea | g | 2.86E+04 | 6.12E+09 | 1.75E+14 | After Brown & Ulgiati 2004 |
| | *Machinery* | | | | | |
| 13 | Steel | g | 9.02E+01 | 3.03E+09 | 2.73E+11 | After Bargigli & Ulgiati 2003 |
| 14 | Cast Iron | g | 1.38E+02 | 2.40E+09 | 3.31E+11 | After Bargigli & Ulgiati 2003 |
| 15 | Aluminum | g | 1.22E+01 | 2.01E+10 | 2.46E+11 | After Buranakarn 1998 |
| 16 | Copper | g | 4.33E+00 | 3.22E+09 | 1.39E+10 | After Lapp 1991 |
| 17 | Non-Renewable fraction of Services | € | 1.15E+04 | 9.60E+11 | 1.11E+16 | Buonocore et al. 2015 |
| 18 | Non-Renewable fraction of Labour | people/yr | 6.69E-04 | 3.46E+16 | 2.31E+13 | After Cialani et al. 2005 |
| | ***Total*** | | | | | |
| 19 | **Electricity from Animal Fat (with L&S)** | MWh | 8.59E-01 | 1.37E+16 | 1.18E+16 | This Work |
| | | J | 3.09E+09 | 3.82E+06 | 1.18E+16 | This Work |
| 20 | **Electricity from Animal Fat (without L&S)** | MWh | 8.59E-01 | 4.08E+14 | 3.50E+14 | This Work |
| | | J | 3.09E+09 | 1.13E+05 | 3.50E+14 | This Work |



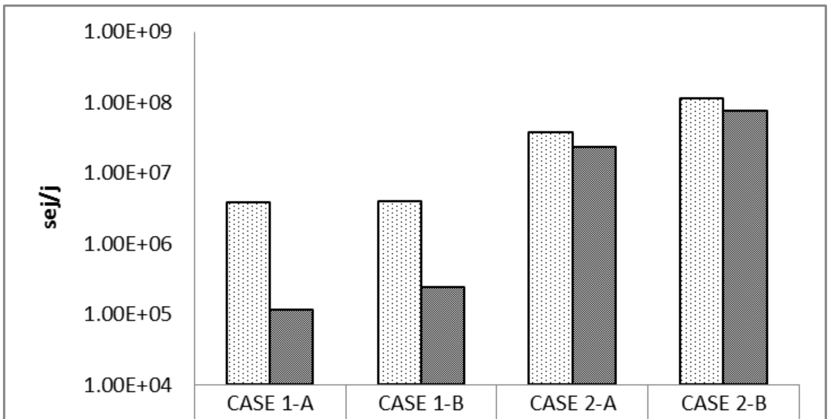

| | CASE 1-A | CASE 1-B | CASE 2-A | CASE 2-B |
|---|---|---|---|---|
| with L&S | 7.56E+08 | 2.49E+09 | 4.41E+11 | 1.45E+12 |
| without L&S | 7.33E+08 | 2.41E+09 | 3.07E+11 | 1.01E+12 |

**Figure 3.7.** UEVs of the animal fat produced by the investigated process.




| | CASE 1-A | CASE 1-B | CASE 2-A | CASE 2-B |
|---|---|---|---|---|
| with L&S | 4.03E+08 | 2.17E+09 | 1.70E+11 | 1.27E+12 |
| without L&S | 3.91E+08 | 2.10E+09 | 1.64E+11 | 8.82E+11 |

**Figure 3.8.** UEVs of the animal meal produced by the investigated process.




| | CASE 1-A | CASE 1-B | CASE 2-A | CASE 2-B |
|---|---|---|---|---|
| with L&S | 3.82E+06 | 3.95E+06 | 3.69E+07 | 1.13E+08 |
| whitout L&S | 1.13E+05 | 2.39E+05 | 2.31E+07 | 7.60E+07 |

**Figure 3.9.** UEVs of the electric energy generated by the investigated process.

Table 3.10a and Table 3.10b summarize the emergy synthesis and the indicators of, respectively, the rendering process and the electricity generation process, with and without L&S.

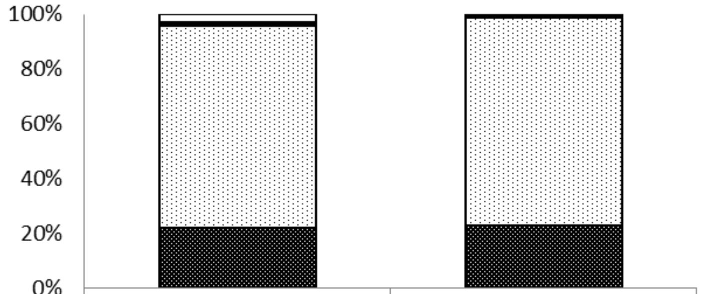
**Table 3.10a.** Emergy synthesis and indicators of the rendering process, with and without L&S

| Without L&S | Unit | CASE 1-A | CASE 1-B | CASE 2-A | CASE 2-B |
|---|---|---|---|---|---|
| $U=R+N+F_R+F_N$ | sej | 1.04E+15 | 1.04E+15 | 4.38E+17 | 4.38E+17 |
| $EYR=U/(F_R+F_N)$ | sej | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 |
| $ELR=(N+F_R+F_N)/(R+F_R)$ | sej | 4.48E+05 | 4.48E+05 | 1.88E+08 | 1.88E+08 |
| ESI=EYR/ELR | sej | 2.23E-06 | 2.23E-06 | 5.32E-09 | 5.32E-09 |
| $\%REN=(R+F_R)/U$ | | 0.00% | 0.00% | 0.00% | 0.00% |
| **With L&S** | **Unit** | **CASE 1-A** | **CASE 1-B** | **CASE 2-A** | **CASE 2-B** |
| $U=R+N+F_R+F_N$ | sej | 1.08E+15 | 1.08E+15 | 4.54E+17 | 6.29E+17 |
| $EYR=U/(F_R+F_N)$ | sej | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 |
| $ELR=(N+F_R+F_N)/(R+F_R)$ | sej | 1.09E+03 | 1.09E+03 | 2.75E+01 | 3.81E+01 |
| ESI=EYR/ELR | sej | 9.20E-04 | 9.20E-04 | 3.63E-02 | 2.62E-02 |
| $\%REN=(R+F_R)/U$ | | 0.09% | 0.09% | 3.63% | 2.62% |

**Table 3.10b.** Emergy synthesis and indicators of the electricity generation process, with and without L&S.

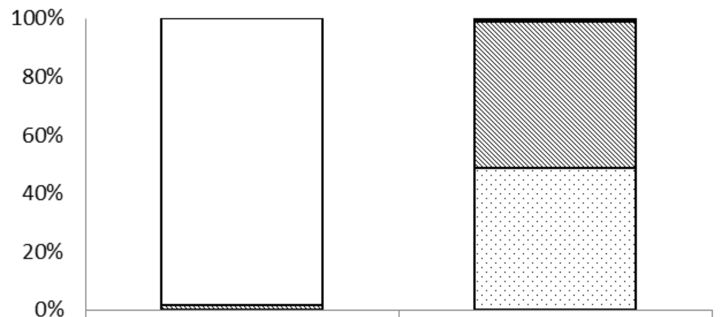
| Without L&S | Unit | CASE 1-A | CASE 1-B | CASE 2-A | CASE 2-B |
|---|---|---|---|---|---|
| $U=R+N+F_R+F_N$ | sej | 3.50E+14 | 7.41E+14 | 7.16E+16 | 2.35E+17 |
| $EYR=U/(F_R+F_N)$ | sej | 1.95E+00 | 4.11E+00 | 3.97E+02 | 1.31E+03 |
| $ELR=(N+F_R+F_N)/(R+F_R)$ | sej | 9.23E+05 | 5.92E+05 | 1.88E+08 | 1.88E+08 |
| ESI=EYR/ELR | sej | 2.11E-06 | 6.94E-06 | 2.11E-06 | 6.94E-06 |
| $\%REN=(R+F_R)/U$ | | 0.00% | 0.00% | 0.00% | 0.00% |
| **With L&S** | **Unit** | **CASE 1-A** | **CASE 1-B** | **CASE 2-A** | **CASE 2-B** |
| $U=R+N+F_R+F_N$ | sej | 1.18E+16 | 1.22E+16 | 1.14E+17 | 3.49E+17 |
| $EYR=U/(F_R+F_N)$ | sej | 1.02E+00 | 1.05E+00 | 9.82E+00 | 3.00E+01 |
| $ELR=(N+F_R+F_N)/(R+F_R)$ | sej | 3.44E+01 | 3.55E+01 | 2.71E+01 | 3.70E+01 |
| ESI=EYR/ELR | sej | 2.95E-02 | 2.96E-02 | 3.62E-01 | 8.12E-01 |
| $\%REN=(R+F_R)/U$ | | 2.91% | 2.82% | 3.56% | 2.63% |

In Table 3.10a, U, from CASE 1 (A and B) to CASE 2 (A and B) both without and with L&S, increases of two orders of magnitude, while in Table 3.10b it increases of two orders of magnitude without L&S, and of one order of magnitude including L&S. In Table 3.10a, from CASE 1 to CASE 2, the ELR increases of three orders of magnitude without L&S, while it decreases of two orders of magnitude whit L&S. In Table 3.10b the ELR increases of three orders of magnitude from CASE 1 to CASE 2 without L&S, while it remains stable when including L&S. ESI decreased of three orders of magnitude in Table 3.10a without L&S, and increases of two orders of magnitude with L&S, from CASE 1 to CASE 2. It remains stable in Table 3.10b without L&S, while it increases of 1 order of magnitude, with L&S, from CASE 1 to CASE 2. Both in Table 3.10a and 3.10b, higher renewability is connected to the inclusion of L&S, because of the renewable fraction of L&S. Figure 3.10 and Figure 3.11 show the percentage contribution of the input flow to U of, respectively, the rendering process and the electricity generation process, with and without L&S. From Figure 3.10 the large contributions coming from the fossil fuels is clear: methane is contributing for more than 70% and diesel more than 20% with and without L&S. Figure 3.11 shows how important is the contribution of L&S in the electricity generation process, while without L&S, the major contributions come from urea and fat, both around 50%.




| | with L&S | without L&S |
|---|---|---|
| L&S | 3.06% | 0% |
| MACHINERY | 1.40% | 1.44% |
| METHANE | 73.65% | 75.97% |
| DIESEL | 21.89% | 22.58% |

**Figure 3.10**. Percentage contributions to U from input flows within the rendering process (CASE 1-A).




| | with L&S | without L&S |
|---|---|---|
| L&S | 98.45% | 0% |
| DIESEL+OIL | 0.03% | 1.33% |
| UREA | 1.52% | 50.07% |
| FAT | 0% | 48.60% |

**Figure 3.11.** Percentage contributions to U from input flows within the electricity generation process (CASE 1-A).

The presented results show how the perspective used to analyze a chosen system affect the evaluation of the process performance. From a methodological point of view, it is of paramount important to make a decision about the way waste materials should be considered in a process evaluation (Bala Gala et al., 2015). Although LCA is a "cradle to grave" approach, it clearly appears that waste and residues are a special category of flows that deserve a different consideration than primary input flows and non-recyclable emissions. While designing an evaluation method (Bala Gala et al., 2015) suitable for processes dealing with waste processing for resource recovery, it should not be disregarded that the investigated process is not a theoretical scenario, but instead a real industrial plant designed and managed within a circular economy oriented company. The process is already active and generates electric energy that is entered in the Italian grid, heat and other by-products. In emergy, when the animal by-products are considered as waste, and a 'zero burden' approach is used, meaning that the material enters the process without the burdens related to the livestock and slaughtering phases (CASE 1-A and CASE 1-B), the electricity generated shows better performances than the Italian mix of electric energy, which shows a UEV of 2.52E+05 sej/J (after Brown & Ulgiati 2004).
The presented results show that the investigated process should not be considered an electricity production process. The process is not seen as purposefully oriented to generate a 'fuel' (i.e. the residues) to be used for electricity generation purpose, but instead electricity is seen as an additional advantage gained when dealing with treatment and disposal of waste organic material. This study was performed keeping in mind an idea of circularity (Ghisellini et al., 2015). Waste prevention, efficiency increase, resource exchange, reuse and recycle across scales, as well as eco-design of processes and products for easy optimization of resource use, are all concepts and tools that contribute to get out of the old paradigm 'take, make and dispose' towards a more environmentally sound production and consumption system.

*Conclusions*

The holistic perspective adopted in this study allowed a comprehensive assessment of the environmental impacts and benefits of the electricity production from AFW, exploring constraints and potentialities of the investigated system.
In this work, the environmental performances of the production of electricity from animal fats, obtained from a rendering process of animal by-products, was shown. The presented results prove that the 'zero-burden' approach to waste disposal is the most reasonable framework for dealing with waste treatment and conversion to useful output flows of energy and matter, and that, in such perspective, the electricity obtained is more environmentally sound than, among others, the average grid electricity mix.
The investigated process shows to be capable to process animal residues and to separate the protein fraction destined to animal meal and chemicals, from a residual animal fat fraction destined to electricity generation, within a bio-refinery perspective company. The assessment of costs and benefits by means LCA and emergy accounting

shows that recovery of electricity and matter is beneficial from both environmental and energy points of view and suggests further steps towards increased circularity. Results are based on a real case plant, which makes them much stronger and reliable than just a feasibility scenario.

A circular economy and technology framework is advocated in the study, where resource use is optimized over the entire production chain in order to make the best out of limited resources. Such efficiency increase is foreseen within a new paradigm for sustainable production and consumption, where lifestyles for resource optimization (e.g. diet, in the investigated case) are also an important aspect of the expected environmental improvement, to complement technological options for energy and material recovery.

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# CHAPTER 4 – PAPER-MAKING AND PAPER-RECYLING INDUSTRY

## Efficiency and sustainability indicators for papermaking from virgin pulp. An emergy-based case study

### Introduction

The pulp and paper industry is one of the largest industries in the world, with very high capital investments. In 2014 the world's total paper production amounted to 406 million tons. Asia which accounts for 45% (179 million tons) of paper production, is by far the largest paper producer. Europe (107 million tons) and North America (85 million tons) are also significant producers (Bajpai, 2015). In particular, in Europe in 2015, the eight leading paper and board producing countries were Germany (24.9%), Finland (11.4%), Sweden (11.2%), Italy (9.7%), France (8.8%), Spain (6.8%), Austria (5.5%) and Poland (4.8%). As regards the grade, more than half of the paper and board product mix is packaging and wrapping paper and board (53%); about 31% is office paper, the remainder is newsprint, household and sanitary paper (CEPI, 2016).
Industrial production of pulp and paper is an intensive consumer of energy (fossil fuels, electricity), natural resources (water, wood) and chemicals (Avşar and Demirer, 2008). The pulp and paper industry accounts for approximately 6% of total industrial energy consumption and 2% of direct carbon dioxide ($CO_2$) emissions from industrial sector worldwide (IEA, 2016). Although the pulp and paper industry ranks fourth in terms of energy consumption among industries, it is one of the least $CO_2$-intensive industries because the widely production and utilization of renewable energy within this sector (around 50% of the primary energy consumption comes from biomass) (BREF, 2015). Also, half of the paper produced comes from recycled fibre. This evolution has resulted in that, from 1991 to 2015, direct absolute $CO_2$ emissions have decreased by 18.2 %, whereas the pulp and paper production has increased by 50% and 22%, respectively (CEPI, 2016). However, given the projected continuing increase in pulp and paper production, future reductions (e.g., by 2030 or 2050) in energy use and $CO_2$ emissions will require additional innovations beyond the technologies available for implementation today. Innovations will likely include development of different processes and materials for pulp and paper production or technologies that can economically capture and store the $CO_2$ emissions. Thus, the definition of the environmental profile of this industry will be a key element in the pulp and paper industry's midand long-term climate change mitigation strategies.
A sustainability perspective should rely on a wider and holistic viewpoint, properly including all direct and indirect interactions with the environment. To this purpose, the

emergy (spelled with “m”) analysis method is very appropriate for the evaluation of the efficiency, effectiveness and sustainability of the papermaking process under different perspectives (resource quality, time and spatial scales). Several studies concerning environmental impacts, eco-efficiency, and cleaner technologies in the pulp and paper sector have already been carried out (Lopes et al., 2003; Dias et al., 2007; Hong et al., 2011; Kong et al., 2016, among others), but none of them addressed resource quality and resource generation costs from a supply-side point of view. This study aims at filling the gap. The largest supply-side environmental costs are generated by the industrial processing activities, due to high energy and water consumption as well as to the significant use and release of chemicals and combustion products. Only a minor role is played by forestry activities that supply the raw feedstock, although forestry management practices certainly affect both the final productivity and the energy balance, through the amount and use efficiency of the farm inputs.
By means of Emergy Accounting (EMA) performance indices, this study aims to assess the environmental sustainability associated to the production of office paper so as to identify those process steps that entail the highest environmental loads and require improvements. Three forest management scenarios – based on poplar, eucalyptus and spruce/pine production for raw material supply – were evaluated to assess the sustainability and the efficiency of each species. In particular, the marginal costs of achieving higher energy and material efficiency are investigated and a special focus is placed on the identification of the impacts of energy input flows on additional demand for environmental services.

*Materials and methods*

This study was performed using a methodological framework based on Emergy Accounting (Odum, 1996). The total value for emergy includes all the resources and services used for obtaining a product, process or service, whether they come from the environment or from the economy. For analysis, some energy diagrams are designed to identify all the material and energy flows that make the system. This methodology uses its own algebra with which it is possible calculate indexes from the relations between the resources that make the studied system. The emergy is measured in joules of solar emergy, which makes it possible to account the flows from the environment and the economy on a common basis, the sej (solar emergy joules). The Unit Emergy value (UEV) defines the quantity of emergy (sej) that is need for obtaining one gram (specific emergy) or one joule (transformity) of a product, process or service, whether it’s natural or anthropogenic. Once the UEV of a product is defined, it’s possible to calculate the direct and indirect solar energy necessary for its obtainment.

*System description and boundaries*

The papermaking process under study was divided into the following phases: forestry (includes the production of poplar, eucalyptus and spruce/pine plantations respectively in Italy, Brazil and Scandinavia); unbleached pulp production; bleached pulp production; paper production (includes office paper production). It should be noted that the manufacturing of paper integrated with the manufacturing of pulp was assumed in this study.

The emergy analysis starts with the design of energy diagrams. The study of the diagrams makes it possible to identify the boundaries established for the studied systems and its main components and also the interactions between them. The emergy system diagram in Figure 4.1 shows the forestry sub-system that provides timber to the Pulp & Paper production sub-system as well as to the market and wood residues to the energy sector for electricity production. The forestry subsystem includes: silviculture operations (site preparation, stand establishment and tending), logging operations (harvesting and forwarding), debarking, chipping and secondary hauling (transport from forest landing to pulp and paper mills gate). Renewable sources (sun, wind, rain, deep heat) are shown as flowing to the system from the left side of the diagram. Renewable inflows shown in Figure 4.1 go directly in support of the investigated system, and indirectly of the pulp and paper production through timber harvest. In addition to renewable flows, further imported flows from the main economy (fertilizers, chemicals, fuels & electricity, goods & machinery and labor) support forestry sector and pulp & paper production. These human-managed flows are shown as inflowing from the top of the diagram.

The diagram in Figure 4.2 focuses on the sub-sector of pulp and paper production. Manufacturing of pulp and paper is not a single process but a series of unit processes, often linked and interdependent. In the papermaking process, wood logs are first debarked and chipped into small pieces or "woodchips". Then water and heat are added, and by mechanical or chemical processes, the wood is separated into individual fibres (digesting). Specifically, the chemical pulp-making process was considered in this study as it is the dominant due to the high quality of pulps obtained with low lignin content and lower energy consumption (Das and Houtman, 2004; CEPI, 2016). Furthermore, this process is ideal for all office papers (EPA U.S., 2009). The spent liquor and its dissolved contaminants – referred to as "black liquor"– are washed away and sent to the chemical recovery process for energy production. After refining, the raw pulp is whitened by a bleaching process prior to the paper making phase. Then this pulp slurry is sprayed onto a flat wire screen which moves very quickly through the paper machine. Water drains out, and the fibres bond together. The web of paper is pressed between rolls which squeeze out more water and press it to make a smooth surface. Heated cylinders then dry the paper, and the finished paper is slit into smaller rolls (BREF, 2015).

It is worth noting that, in this study, the output of each stage was considered to be the input of the subsequent stage. Moreover, the production and maintenance of capital goods (buildings, pulp and paper machinery, roads, etc.) were excluded from the study, as well as the environmental costs associated with the wastewater and solid waste treatment and the energy production from wood residues.

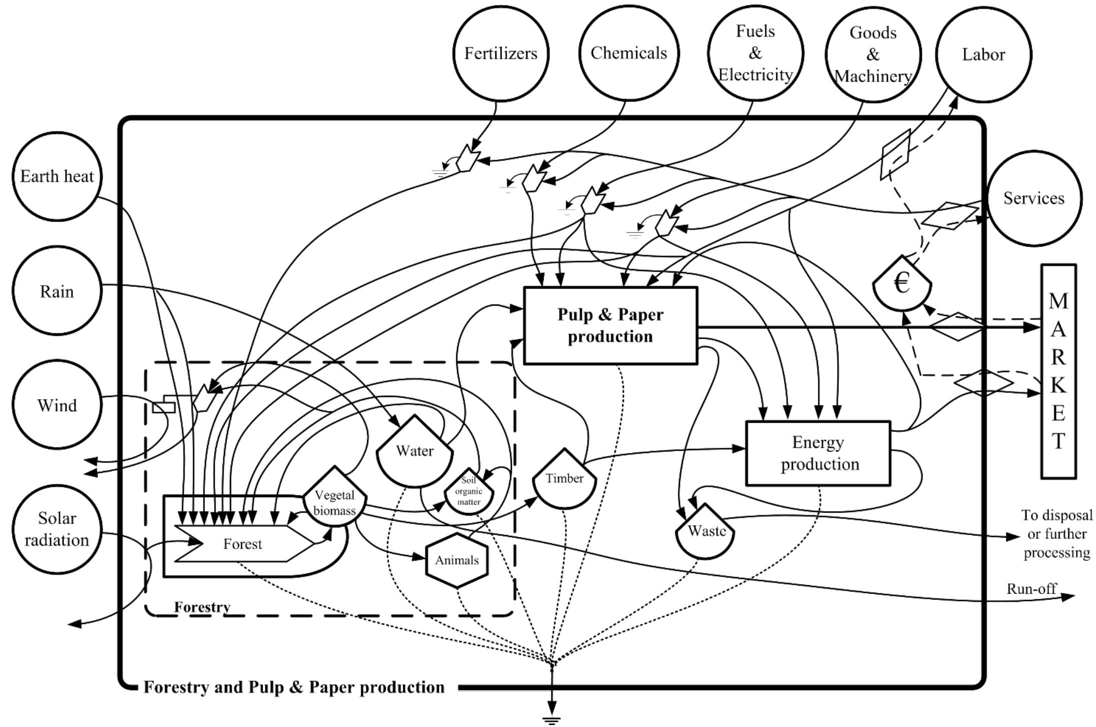


**Figure 4.1.** System diagram of Forestry sector and Pulp & Paper production.

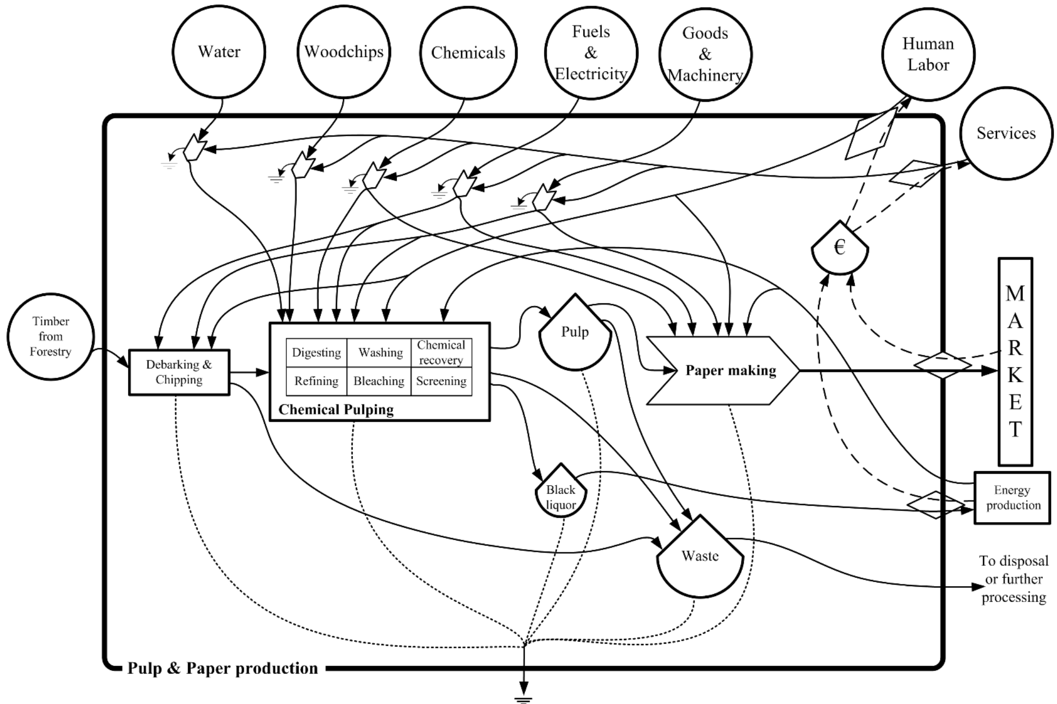


**Figure 4.2.** System diagram of Pulp & Paper production.

*Data collection and basic assumption*

In this study all flows have been properly allocated to the chosen functional unit defined as 1 tonne of produced office paper. The new Biosphere emergy baseline 12.0E+24 sej/yr (i.e. the total renewable annual emergy driving the biosphere; Brown et al., 2016) is referred to for all calculations of flows and indicators.

As regards the different forestry operations for spruce/pine, poplar and eucalyptus, data was obtained from the literature (Doherty, 1995; Bacenetti et al., 2012; Romanelli et al., 2012). The choice of these specific forest systems is motivated by the fact that they are most common species for the manufacturing of paper (Biermann, 1996). Data inventory about the chemicals and energy consumptions used in the pulp and paper making process come from Moore & Moore, 1976 and Giraldo and Hyman (1996), respectively.

Transport of wood from the forest area to the pulp and paper mills was also considered. Transport carried out by road vehicles, trains and ships was used for wood deliveries (Berg and Lindholm, 2005; Net et al., 2011). In this analysis, the total biomass production was considered as a whole. Thus, allocation has not been required since it has been considered that all biomass is chipped and delivered to pulp and paper facilities. The remaining biomass generated in the forest site such as leaves, branches and stumps have not been computed in the analysis as by-products. It has been assumed that they remain in the plantation contributing to improve the soil quality. That perspective is in agreement with other forest-related studies (González-García et al., 2009; Dias and Arroja, 2012).

*Results*

Tables 4.1, 4.2, 4.3, and 4.4 present the inventory of the spruce/pine forestry operations and pulp and paper production. Data regarding the operations for the other forest systems are not shown due to lack of space. Input data were multiplied by suitable UEV to yield the emergy values associated with each input item. Results were calculated also without labor and services (L&S) to provide a result reflecting a pure biophysical accounting not including money flows. Computed UEVs for each phases of the papermaking process are given at the bottom of Tables 4.1, 4.2, 4.3, 4.4 and summarized in Fig. 4.4. As regards the forestry step, the UEV with L&S is 1.36E+04 sej/J and 1.14E+04 sej/J without L&S; as for the pulping phase, the UEV is 2.46E+05 sej/J with L&S and 1.80E+05 sej/J without L&S; with reference to the pulp bleaching step, the UEV is 3.07E+05 sej/J with L&S and 2.13E+05 sej/J without L&S; as to the paper making phase, the UEV is 2.09E+05 sej/J with L&S and 1.46E+05 sej/J without L&S.

**Table 4.1.** Emergy evaluation of boreal spruce and pine forestry operations and woodchips production in Sweden.

| # | Item | Unit | Amount | UEV (sej/unit) | Reference for UEV | Emergy flows (sej) |
|---|---|---|---|---|---|---|
| | ***Local renewable resources*** | | | | | |
| 1 | Solar radiation | J | 3.16E+13 | 1.00E+00 | Odum, 1996 | 3.16E+13 |
| 2 | Wind, kinetic energy | J | 1.07E+11 | 1.00E+03 | US, EPA 2016 | 1.07E+14 |
| 3 | Evapo-transpired rain | J | 2.39E+10 | 7.01E+03 | US, EPA 2016 | 1.68E+14 |
| | ***Purchased resources*** | | | | | |
| | *Silviculture* | | | | | |
| 4 | Diesel fuel | J | 7.33E+07 | 1.43E+05 | After Brown et al., 2011 | 1.04E+13 |
| 5 | Steel for machinery | g | 8.11E+01 | 2.80E+09 | After Bargigli and Ulgiati, 2003 | 2.27E+11 |
| | *Harvesting* | | | | | |
| 6 | Diesel fuel | J | 7.33E+08 | 1.43E+05 | After Brown et al., 2011 | 1.04E+14 |
| 7 | Steel for machinery | g | 2.31E+02 | 2.80E+09 | After Bargigli and Ulgiati, 2003 | 6.46E+11 |
| | *Debarking & Chipping* | | | | | |
| 8 | Diesel fuel | J | 1.71E+09 | 1.43E+05 | After Brown et al., 2011 | 2.43E+14 |
| 9 | Steel for machinery | g | 2.83E+03 | 2.80E+09 | After Bargigli and Ulgiati, 2003 | 7.92E+12 |
| | *Transport woodchips from field to pulp & paper mills* | | | | | |
| 10 | Diesel fuel, by road | J | 1.37E+08 | 1.43E+05 | After Brown et al., 2011 | 1.95E+13 |
| 11 | Diesel fuel, by railway | J | 6.33E+07 | 1.43E+05 | After Brown et al., 2011 | 9.02E+12 |
| 12 | Steel for machinery | g | 1.43E+03 | 2.80E+09 | After Bargigli and Ulgiati, 2003 | 4.00E+12 |
| 13 | Labor | p-year | 2.78E-03 | 1.66E+16 | Viglia et al., 2016 | 4.61E+13 |
| 14 | Services | € | 8.53E+01 | 1.02E+12 | Viglia et al., 2016 | 8.70E+13 |
| | Total Emergy (w/o L&S) | | | | | 7.06E+14 |
| | Total Emergy (with L&S) | | | | | 8.39E+14 |
| | ***Outputs*** | | | | | |
| 15 | Woodchips | g | 3.50E+06 | | | |
| | | J | 6.19E+10 | | | |
| | Specific emergy (w/o L&S) | g | | 2.02E+08 | | |
| | Specific emergy (with L&S) | g | | 2.40E+08 | | |
| | Trasformity (w/o L&S) | J | | 1.14E+04 | | |
| | Trasformity (with L&S) | J | | 1.36E+04 | | |

**Table 4.2.** Emergy evaluation of unbleached pulp production referred to 1 ton of produced paper.

| # | Item | Unit | Amount | UEV (sej/unit) | References for UEV | Emergy flows (sej) |
|---|---|---|---|---|---|---|
| | ***Local renewable resources*** | | | | | |
| 1 | Solar radiation | J | 7.37E+10 | 1.00E+00 | Odum, 1996 | 7.37E+10 |
| | ***Local non-renewable resources*** | | | | | |
| 2 | Process water | J | 2.37E+08 | 8.76E+04 | After Odum, 1996 | 2.07E+13 |
| | ***Purchased resources*** | | | | | |
| 3 | Woodchips | J | 6.19E+10 | 1.14E+04 | This study | 7.06E+14 |
| 4 | Sodium sulfate ($Na_2SO_4$) | g | 2.69E+04 | 3.19E+06 | US, EPA 2016 | 8.58E+10 |
| 5 | Limestone ($CaCO_3$) | g | 5.54E+03 | 5.26E+08 | US, EPA 2016 | 2.92E+12 |
| 6 | Lime 1 (CaO) | g | 1.29E+04 | 5.26E+08 | US, EPA 2016 | 6.81E+12 |
| 7 | Sulphur | g | 1.38E+04 | 8.51E+08 | US, EPA 2016 | 1.18E+13 |
| 8 | Sodium carbonate ($Na_2CO_3$) | g | 1.13E+04 | 2.62E+09 | After Campbell and Lu, 2009 | 2.97E+13 |
| 9 | Ammonia | g | 1.79E+03 | 3.43E+08 | After Ulgiati, 1996 | 6.16E+11 |
| 10 | Magnesium | g | 1.38E+03 | 3.82E+09 | US, EPA 2016 | 5.26E+12 |
| 11 | Electricity | J | 9.67E+08 | 2.18E+05 | This study | 2.11E+14 |
| 12 | Fuel for process step | J | 1.29E+09 | 5.56E+04 | This study | 7.17E+13 |
| 13 | Fuel for process steam | J | 3.83E+09 | 5.56E+04 | This study | 2.13E+14 |
| 14 | Labor | p-year | 1.24E-03 | 1.66E+16 | Viglia et al., 2016 | 2.05E+13 |
| 15 | Services | € | 4.46E+02 | 1.02E+12 | Viglia et al., 2016 | 4.54E+14 |
| | Total Emergy (with L&S) | | | | | 1.75E+15 |
| | Total Emergy (w/o L&S) | | | | | 1.28E+15 |
| | ***Outputs*** | | | | | |
| 16 | Wood pulp | g | 9.90E+05 | | | |
| | | J | 7.13E+09 | | | |
| | Specific emergy (with L&S) | g | | 1.77E+09 | | |
| | Specific emergy (w/o L&S) | g | | 1.29E+09 | | |
| | Transformity (with L&S) | J | | 2.46E+05 | | |
| | Transformity (w/o L&S) | J | | 1.80E+05 | | |

**Table 4.3.** Emergy evaluation of bleached pulp production referred to 1 ton of produced paper.

| # | Item | Unit | Amount | UEV (sej/unit) | References for UEV | Emergy flows (sej) |
|---|---|---|---|---|---|---|
| | ***Local renewable resources*** | | | | | |
| 1 | Solar radiation | J | 7.37E+10 | 1.00E+00 | Odum, 1996 | 7.37E+10 |
| | ***Purchased resources*** | | | | | |
| 2 | Unbleached pulp | J | 7.13E+09 | 1.80E+05 | This study | 1.28E+15 |
| 3 | Chlorine | g | 1.06E+04 | 3.43E+08 | After Ulgiati, 1996 | 3.64E+12 |
| 4 | Caustic soda (sodium hydroxide) | g | 5.51E+03 | 7.66E+09 | After Fahd et al., 2012 | 4.22E+13 |
| 5 | Lime 2 (CaO) | g | 4.29E+03 | 5.26E+08 | US EPA, 2016 | 2.26E+12 |
| 6 | Sodium and calcium hypochlorite | g | 4.10E+03 | 7.66E+09 | After Ulgiati, 1996 | 3.14E+13 |
| 7 | Sulfuric acid | g | 1.63E+03 | 8.95E+08 | After Ingwersen, 2010 | 1.46E+12 |
| 8 | Sodium chlorate | g | 9.94E+02 | 3.43E+08 | After Ulgiati, 1996 | 3.41E+11 |
| 9 | Electricity | J | 1.38E+08 | 2.18E+05 | This study | 3.00E+13 |
| 10 | Fuel for process steam | J | 2.35E+09 | 5.56E+04 | This study | 1.31E+14 |
| 11 | Labor | p-years | 1.24E-03 | 1.66E+16 | Viglia et al., 2016 | 2.05E+13 |
| 12 | Services | € | 6.30E+02 | 1.02E+12 | Viglia et al., 2016 | 6.43E+14 |
| | Total Emergy (with L&S) | | | | | 2.19E+15 |
| | Total Emergy (w/o L&S) | | | | | 1.52E+15 |
| | ***Outputs*** | | | | | |
| 13 | Bleached pulp | g | 9.90E+05 | | | |
| | | J | 7.13E+09 | | | |
| | Specific emergy (with L&S) | g | | 2.21E+09 | | |
| | Specific emergy (w/o L&S) | g | | 1.54E+09 | | |
| | Transformity (with L&S) | J | | 3.07E+05 | | |
| | Transformity (w/o L&S) | J | | 2.13E+05 | | |

**Table 4.4.** Emergy evaluation of 1 ton of produced office paper.

| # | Item | Unit | Amount | UEV (sej/ unit) | References for UEV | Emergy flows (sej) |
|---|---|---|---|---|---|---|
| | ***Local renewable resources*** | | | | | |
| 1 | Solar radiation | J | 7.37E+10 | 1.00E+00 | Odum, 1996 | 7.37E+10 |
| | ***Local non-renewable resources*** | | | | | |
| 2 | Process water | J | 1.15E+09 | 8.76E+04 | After Odum, 1996 | 1.00E+14 |
| | ***Purchased resources*** | | | | | |
| 3 | Bleached pulp | J | 7.13E+09 | 2.13E+05 | This study | 1.52E+15 |
| 4 | Chemicals | | | | | |
| 4.1 | China clay (kaolin) | g | 2.72E+04 | 2.54E+09 | After Buranakarn, 1998 | 6.93E+13 |
| 4.2 | Starches | g | 1.68E+04 | 6.78E+04 | After Yan and Odum, 2001 | 1.14E+09 |
| 4.3 | Aluminum sulfate hydrate | g | 1.22E+04 | 2.01E+09 | After De Moraes et al., 2004 | 2.46E+13 |
| 4.4 | Rosin | g | 4.36E+03 | 4.83E+08 | After Odum, 1996 | 2.11E+12 |
| 4.5 | Waxes | g | 2.76E+03 | 3.40E+09 | After Bastianoni et al., 2009 | 9.36E+12 |
| 4.6 | Titanium dioxide | g | 1.54E+03 | 1.01E+07 | US EPA, 2016 | 1.55E+10 |
| 4.7 | Wet-strength polymer resins | g | 6.09E+02 | 6.70E+09 | After Buranakarn, 1998 | 4.08E+12 |
| 4.8 | Slimicides (mercurials, etc) | g | 2.88E+02 | 4.83E+08 | After Odum, 1996 | 1.39E+11 |
| 5 | Electricity | J | 2.00E+09 | 2.18E+05 | This study | 4.36E+14 |
| 6 | Fuel for process steam | J | 8.17E+09 | 5.56E+04 | This study | 4.54E+14 |
| 7 | Labor | p-years | 9.03E-04 | 1.66E+16 | Viglia et al., 2016 | 1.50E+13 |
| 8 | Services | € | 1.10E+03 | 1.02E+12 | Viglia et al., 2016 | 1.12E+15 |
| | Total Emergy (with L&S) | | | | | 3.76E+15 |
| | Total Emergy (w/o L&S) | | | | | 2.62E+15 |
| | ***Outputs*** | | | | | |
| 9 | Paper | g | 1.00E+06 | | | |
| | | J | 1.80E+10 | | | |
| | Specific emergy (with L&S) | g | | 3.76E+09 | | |
| | Specific emergy (w/o L&S) | g | | 2.62E+09 | | |
| | Transformity (with L&S) | J | | 2.09E+05 | | |
| | Transformity (w/o L&S) | J | | 1.46E+05 | | |

The UEVs resulted into 4.55E+05 sej/J for paper production from poplar trees, 1.50E+05 sej/J for paper production from eucalyptus trees and 1.46E+05 sej/J for paper production from spruce/pine trees (Fig. 4.3).

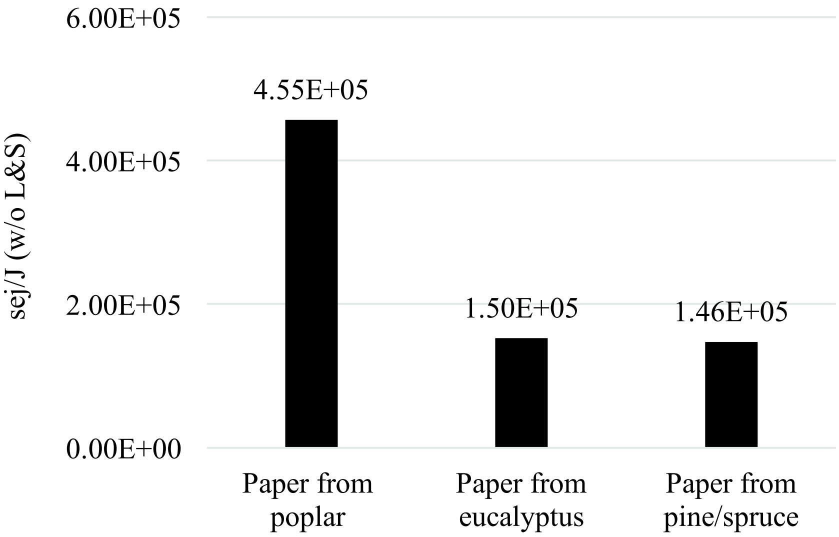


**Figure 4.3.** Comparison between the UEVs of paper made from poplar, eucalyptus and spruce/pine trees.

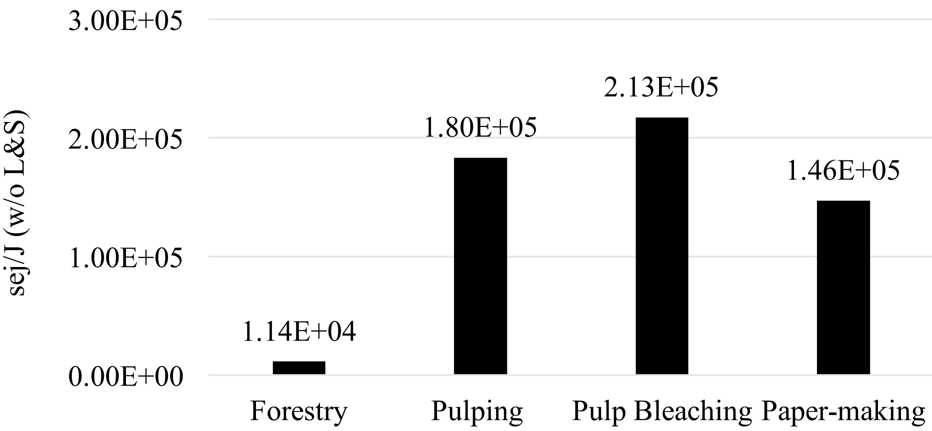


**Figure 4.4.** Comparison between the UEVs of different stages of paper production made from spruce/pine trees.

Fig. 4.5 shows the so-called 'Emergy signatures'– i.e. a bar diagram indicating the relative size of the different categories of input flows – of the phase with highest emergy costs, such as the pulp bleaching, including L&S. The bar diagram of emergy flows shows a large dominance of the unbleached pulp input, the emergy cost of which (58.6% of the total) is much higher than the emergy cost of L&S (30.4 %), fuel for process steam (6.0%), chemicals (3.7%) and electricity (1.4%).

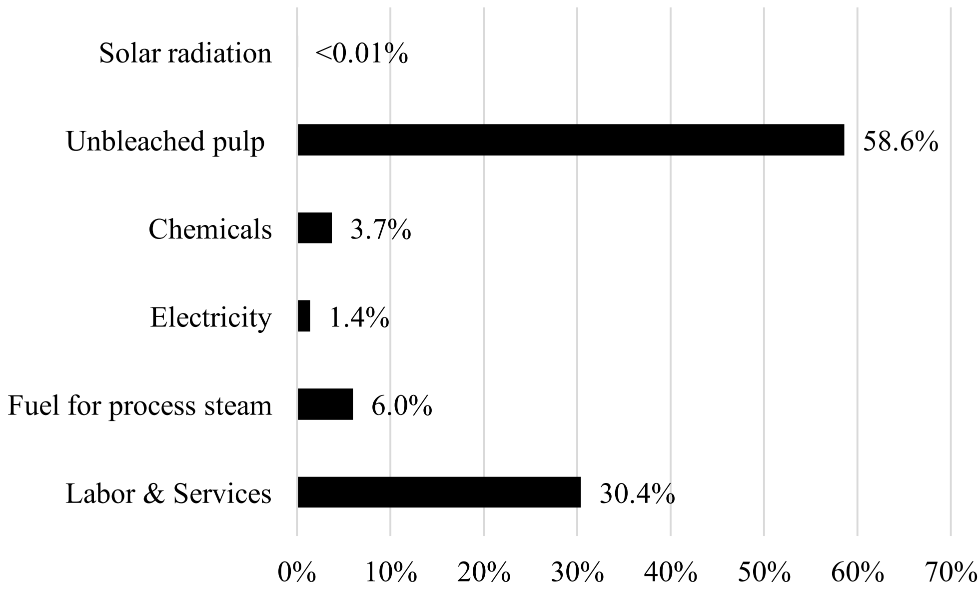


**Figure 4.5.** Emergy signature of pulp bleaching stage.

Finally, Table 4.5 shows emergy synthesis indicators for the papermaking process, respectively calculated with and without accounting labor and services provided to the system.

**Table 4.5.** Emergy Accounting indicators of paper production made from spruce/pine trees.

| Emergy indicators | Value |
|---|---|
| ***With labor and services*** | |
| EYR | 2.59 |
| ELR | 1.26 |
| ESI | 2.06 |
| Renewable fraction (%R) | 50% |
| ***Without labor and services*** | |
| EYR | 3.92 |
| ELR | 0.92 |
| ESI | 4.25 |
| Renewable fraction (%R) | 59.3% |

*Discussion*

Figure 4.3 presents the comparison between the UEVs of the paper produced from different raw material. The type of wood, the machines used in forest operations and the amount of fossil fuels influence the results. Indeed, the values calculated indicate that the forest system based on spruce/pine wood is the one that uses the lowest amount of resources to produce paper. Conversely, the forest system based on poplar trees is the system with the highest UEV with a value that is 3 times bigger than the eucalyptus and spruce/pine system. The value of the UEV is an efficiency index and makes it possible to reckon that the pine/spruce system is more efficient for paper production when we refer to the use of resources. Also, it’s noticeable that the calculated UEVs of paper have the same order of magnitude of the one determined by Doherty (1995), that is 1.15E+05 sej/J.

Furthermore, several stages of papermaking were investigated in this study: forestry, pulp production, bleached pulp production, paper production. As it can be observed in Figs. 4.4 and 4.5, highest emergy costs are due to the pulping operations, in particular to subsequent pulp bleaching stage. In this latter phase, in addition to L&S, also energy and chemicals requirements play an important role. In particular, among chemicals, caustic soda production is identified as an energy-intensive process and very important from an environmental point of view (this result is not shown in the figure). The paper production stage has also an important contribution to emergy investments, mainly due to renewable fuel combustion (bark and black liquor) in the steam production process. Instead, the forestry stage plays a minor role in the environmental costs generated during the paper production process.

Having seen the dominance of pulping step, the definition of improvement options should be focused on that subsystem. Future alternatives in pulp digestion, such as ozone and enzyme delignification, could considerably reduce the consumption of bleaching agents (Jawjit et al., 2007). A recent paper by Skals et al (2008) has concluded that small amounts of enzyme provide the same function as large amounts of chemicals, requiring less fossil fuels consumption than conventional processes and getting environmental improvements. Additionally, according to Shivhare Lal et al (2013) it also is possible to replace the caustic soda (sodium hydroxide) used in pulp bleaching applications with soda ash (sodium carbonate). It has been observed that the soda ash is cheaper, safer and equally effective as caustic soda to produce quality pulp of different grades. Moreover, improvement options regarding energy consumption could also be introduced. The greatest energy-saving potential lies with improving energy distribution and equipment efficiency. If the bleaching equipment was upgraded, the efficiency of bleaching would be improved and, thus, the steam consumption in the digester and the electricity used in refining would be reduced.

Lastly, emergy indicators, such as emergy yield ratio (EYR), environmental load ratio (ELR), environmental sustainability index (ESI) and percent renewable (%R) were used to evaluate the environmental load and local sustainability of the paper production (Table 4.5). Focusing on the EYR index, Table 4.5 shows that the paper production process is characterized by a value equal to 3.92. This latter value confirms a high use of local renewable and local non-renewable inputs versus resources imported from outside of the system. The ELR evaluates the environmental stress, and the lower this index, the lower is the stress imposed to the environment. It’s noticeable that the result obtained by the papermaking step (0.92) indicates a low environmental load. This result is probably due to the fact that the energy consumed by the pulp and paper production processes comes mostly from renewable fuels (biomass). Finally, the index of renewable emergy %R indicates the rate of renewable energy involved on the process. The papermaking step presents a large rate, with 59.3% the renewable energy on its productive chain of its energy flows.

*Conclusion*

In this study the emergy evaluation method was applied to paper manufacturing process in order to identify those process steps that entail the highest environmental loads and require improvements. Different forestry input items were evaluated to assess the sustainability and the efficiency of each option. The results show that the forest system based on spruce/pine wood is the one that uses the lowest amount of resources to produce paper (lower UEV). Furthermore, it was observed that the most relevant stages in environmental costs are due to pulping and papermaking operations related to high chemicals and energy consumption while the forestry activities play a minor role on the whole process. Further research is required to improve and optimize these technologies in order to minimize their energy penalties. Optimizing energy – a crucial step for the process to occur – only requires technical expertise to come into play, while matching a system or process needs with surrounding environment within a sustainability perspective requires a deep knowledge of ecological aspects (rate of topsoil erosion/formation, evapotranspiration, etc.), economic aspects (labor and services), competition for resource use and stakeholders involvement, all of which can be addressed by means of emergy accounting procedures.

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# CHAPTER 5 – URBAN WASTE MANAGEMENT

## The case of waste management in the Metropolitan City of Naples (Italy)

*Introduction*

Municipal Solid Waste (MSW) is an unavoidable by-product of modern societies production and consumption patterns. Due to the exponential growth of human population and the technological development observed since the industrial revolution, the amount of waste produced has continued to grow and the environmental issues associated with vast production of different types of waste have become more critical than ever. In particular, Municipal Solid Waste (MSW), typically including household waste, garden (yard)/park waste and commercial/institutional waste, is expected to double in the next decade (European Parliament and Council, 2008), due to population growth, increasing urbanization and socio-economic development of lowand middle-income countries (Karak et al., 2012; Hoornweg and Bhada-Tata, 2012). MSW is by far the most heterogeneous kind of refuse, being a direct result of the multiplicity of activities in urban environments. Appropriate waste management is therefore a crucial matter, not only because of environmental and human health concerns *per se*, but also as a step ahead towards sustainable production and consumption. The member countries of the European Union (EU) are required to implement waste management systems that comply with a hierarchy of options, over the following order of priority: prevention (in waste generation), preparing for reuse, recycling, other types of recovery (including energy) and, finally, disposal (Directive on Waste 2008/98/EC of the European Parliament and Council of 19th November 2008). Moreover, sending biodegradable organic matter to landfill must be phased out gradually, in line with the targets set out by the Directive on the Landfill of Waste 1999/31/EC of the Council of 26th April 1999. Nevertheless, despite improved legislation and regulatory systems, public acceptance of the location of new waste disposal and treatment facilities is still very low, due to concerns about adverse effects on the environment and human health. Within this context, sustainable MSW management needs support by suitable environmental assessment methods that evaluate the environmental feasibility of waste management strategies. The European Commission calls for increased use of Life Cycle Thinking (European Parliament and Council, 2008) to complement the waste hierarchy of priorities. The Life Cycle Assessment (LCA) method (ISO, 2006a, 2006b) provides an excellent framework for evaluating waste management strategies: through its holistic perspective in quantifying environmental impacts, it was proved very helpful in identifying appropriate solutions for managing solid waste (Laurent et al., 2014). This paper investigates the environmental impacts of the and potentially future systems for managing waste flows, so as to determine the most efficient waste management system for the Metropolitan City of Naples, Italy.

## Materials and Methods

Naples is a metropolitan area in Campania Region, Southern Italy, with a population of about 3 million people, being the 10$^{th}$-most populous urban area in the European Union. Metropolitan City of Naples includes 92 different municipalities which differ in some organizational functions, such as the type of separate collection. In 2012 (reference year of the study) a total MSW production of 1.46E+09 kg/yr (ARPAC Environmental Protection Agency in Campania Region, 2014) is reported and a separate collection system is used to recover around 37% of the total production of MSW. The waste streams included in the analysis are: paper and cardboard, plastic, glass, metal, organic fraction (OFMSW) and mixed municipal solid waste (MMSW). 'Other' fraction, including bulky municipal waste and old electrical appliances (WEEE) and furniture, for which different and separate collection systems are implemented, is not investigated in this study. The model of MSW collection in Naples was based on a combination of two different methods of source separation depending on the area and its characteristics: door-to-door and kerb-side collection. After being collected, the waste flows undergo different treatment and disposal processes in Campania Region or abroad. The treatment and disposal facilities in Campania Region include: seven mechanical and biological treatment (MBT) plants, for a total treatment capacity of about 7,700 t/d, two active landfills, a WtE plant (located in Acerra municipality) with a nominal capacity of 600,000 t/yr (moving grate furnace technology), a number of storage and sorting platforms, and recycling plants belonging to the chain of separate collection. OFMSW is almost completely sent outside Campania Region because of the lack of sufficient local treatment plants (i.e. composting and anaerobic digestion). More details regarding the treatment of the different fractions are provided in the Figure 5.1 (Ripa et al., 2016).

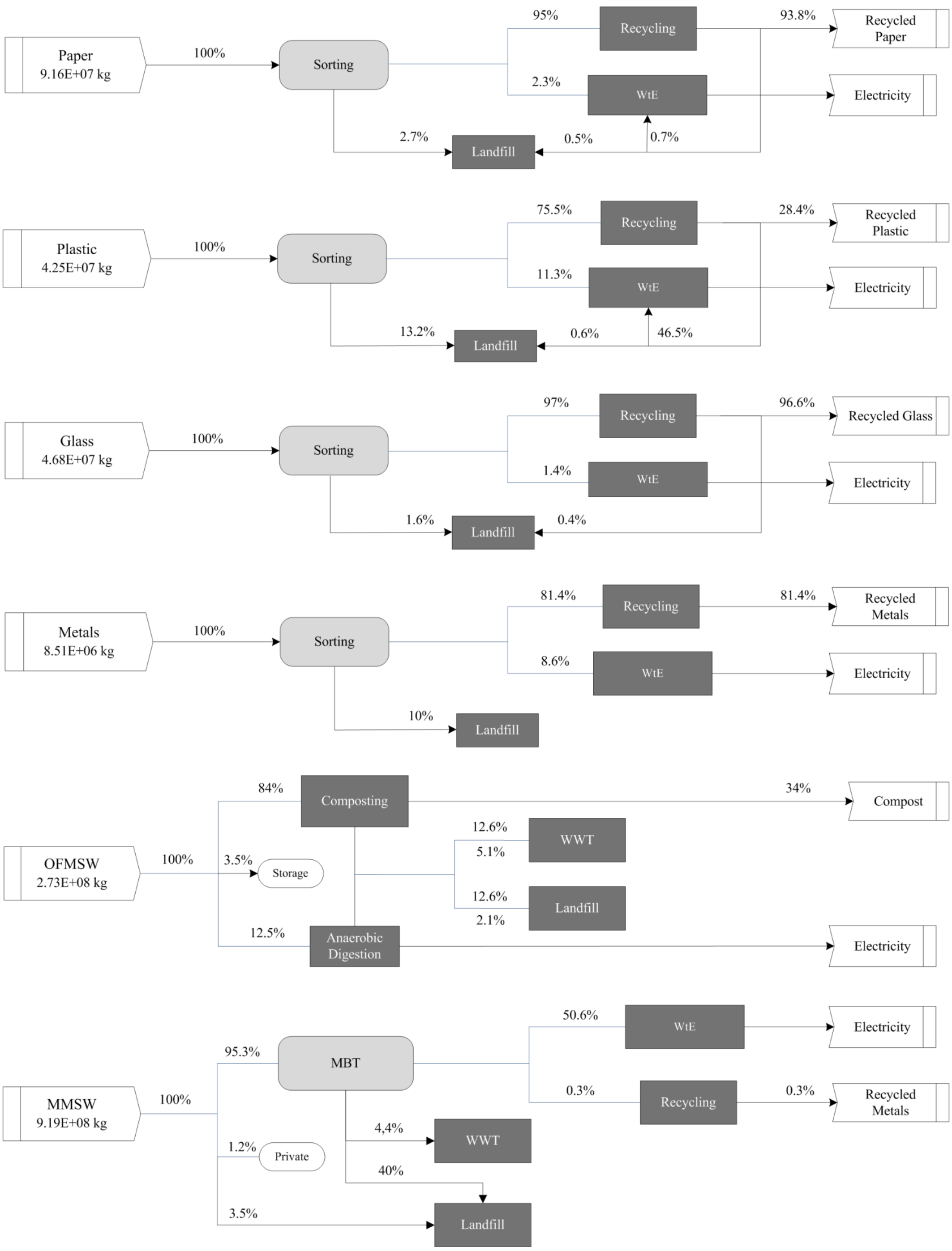



**Figure 5.1**. Mass balance flow chart showing MSW management in Naples in 2012: sorting and pre-treatment steps in grey color, final treatments in dark grey. For OFMSW the two sets of values refer to the percentages of residuals, from composting (top value) and from anaerobic digestion (bottom value), sent to WWT and landfill.

## Goal and scope

This LCA study was performed to analyze the environmental impacts of different MSW management strategies that may be implemented in the Metropolitan City of

Naples, given the imminent end-of-life of the existing landfills. The methodological framework used in this paper is the LCA as defined by ISO standards and ILCD Handbook guidelines (ISO 2006a, b). The functional unit chosen for this assessment is the treatment of the entire mass of MSW produced in the Metropolitan City of Naples in 2012 (1.38E+06 tons/yr): all materials, emissions, energy consumption, and recovery levels are referred to the disposal of this amount of waste. The boundaries of the system under study are not limited to the physical and geographical boundaries of the Metropolitan City but are extended to encompass the whole waste chain: from the generation of waste (zero burden approach) to final disposal of residual waste (i.e. waste that does not undergo further treatment).

Life Cycle Inventory

In this study, data from different sources have been used. Most of the data used (e.g. MBT, Acerra WtE, sorting platforms operation, transportation routes) are primary, i.e. acquired directly from the plant and transport operators. Conversely, secondary data regarding materials' recycling processes, i. e. plastic, metals and paper recycling, were gathered from previous Italian studies (Blengini et al., 2008; Blengini et al., 2012) and from Ecoinvent database.

*Future scenarios description*

Besides the evaluation of the current situation, this study assesses the environmental implications of three different scenarios, which differ by source separation extent and destination of waste for treatment: 35% (S-0), 50% (S-1) and 65% (S-2). For further details, see: Ripa et al., 2016.

**Table 5.1**. Interception efficiencies assumed for the alternative scenarios 50% (S-$1_{a,b}$) and 65% (S-$2_{a,b}$) of source separation level.

| | **SCENARIO $1_{a,b}$ SC 50%** | | | **SCENARIO $2_{a,b}$ SC 65%** | | |
|---|---|---|---|---|---|---|
| Waste fraction | Amount (kg) | Total (%) | Interc. ($\%_i$) | Amount (kg) | Total (%) | Interc. ($\%_i$) |
| MMSW | 7.29E+08 | 50% | | 5.16E+08 | 35% | |
| OFMSW | 3.92E+08 | 27% | 75% | 4.89E+08 | 34% | 90% |
| Paper | 1.27E+08 | 9% | 45% | 1.83E+08 | 13% | 60% |
| Glass | 5.18E+07 | 3% | 65% | 5.83E+07 | 4% | 70% |
| Plastic | 6.66E+07 | 5% | 40% | 1.08E+08 | 7% | 60% |
| Metals | 1.31E+07 | 1% | 30% | 2.29E+07 | 2% | 50% |
| Other* | 7.70E+07 | 5% | 20% | 7.70E+07 | 5% | 20% |

*not included in the analysis

The b-scenarios (S-$0_b$, S-$1_b$, S-$2_b$) pursue the proximity principle according to which the majority of waste should be treated and managed within the region in which it is generated. In order to reach the self-sufficiency, a further expansion of the capacity-building is required. A particular challenge exists with regard to OFMSW and RFMSW which require greatly increased treatment capacity. Regional authorities have carried out feasibility studies in order to identify the best locations for new plants. These studies were used in this work to identify five industrial areas[20], within the Metropolitan City of Naples, where the new plants would be expected. In accordance with the Regional Plan, the treatment capacity required for OFMSW was assumed to be covered (partially in $S\text{-}1_b$ and completely in $S\text{-}2_b$) by converting MBT in composting and sorting plants, in the scenarios with increased level of separate collection. Moreover the Regional Plan recommends a new WtE plant which is however considered only in $S\text{-}0_b$ and $S\text{-}1_b$, whilst the considerable reduction of MMSW in $S\text{-}2_b$ turns in a lessened request for MBT and WtE facilities.

Life Cycle Impact Assessment

SimaPro software version 8.0.5.13 was used to carry out the LCA. The Ecoinvent v3.1 (2015) database was preferred to obtain the environmental loads associated with the materials, transport and energy employed in the study. Among the impact assessment methods, the ReCiPe Midpoint (H) v.1.12 (http://www.lcia-recipe.net/) was chosen, considering that it includes several midpoint indicators. Environmental indicators were chosen according to ISO (2006) recommendations: Global Warming Potential (GWP, in kg $CO_2$ eq), Terrestrial Acidification Potential (TAP, in kg $SO_2$ eq), Freshwater Eutrophication Potential (FEP, in kg P eq), Human Toxicity Potential (HTP, in kg 1,4-DB eq), Photochemical Oxidant Formation Potential (POFP, in kg NMVOC), Terrestrial Ecotoxicity Potential (TEP, kg 1,4-DB eq), Metal Depletion Potential (MDP, in kg Fe eq), Fossil Depletion Potential (FDP, in kg oil eq).

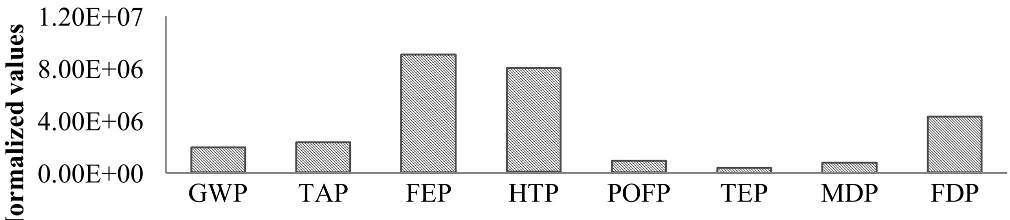
*Results and Discussion*

The current, business-as-usual scenario of MSW management was firstly assessed as baseline in order to model physical flows, resources consumption and emissions to the environment, with reference to the treatment of MSW produced in the Metropolitan City of Naples in 2012. The characterized results of the impact assessment of Scenario 0 (the actual solid waste management system in Naples) are shown in Table 5.2. Hereby all LCA results are disaggregated to visualize the contributions of each waste fraction to the environmental loads. Table 5.2 shows that MMSW is responsible for the highest contribution to all impact categories, accounting always for at least 96% (in POFP) of total impact. OFMSW shows its highest impacts in the POFP category (3% of total impact), whilst the contributions of each RFMSW (plastic, paper, metal, glass) never overcome 1% of total impact.

**Table 5.2**. Recipe Midpoint (H) characterized impacts calculated for MSW management in the Metropolitan City of Naples, with reference to 1.38E9 tons of waste treated in 2012 (scenario S-$0_a$).

| Impact category | Unit | Paper Cardboard | Metals | Plastic | Glass | OFMSW | MMSW | Total |
|---|---|---|---|---|---|---|---|---|
| GWP | kg $CO_2$ eq | 1.73E+07 | 6.62E+06 | 6.13E+07 | 4.07E+07 | 2.18E+08 | 2.17E+10 | 2.20E+10 |
| TAP | kg $SO_2$ eq | 9.12E+04 | 3.16E+04 | 5.28E+04 | 1.72E+05 | 9.35E+05 | 7.94E+07 | 8.06E+07 |
| FEP | kg P eq | 1.76E+03 | 2.83E+03 | 1.88E+03 | 2.49E+03 | 4.88E+03 | 3.75E+06 | 3.76E+06 |
| HTP | kg 1.4-DB eq | 3.53E+06 | 1.22E+07 | 9.94E+06 | 3.12E+06 | 2.43E+07 | 4.99E+09 | 5.04E+09 |
| POFP | kg NMVOC | 8.78E+04 | 2.45E+04 | 6.62E+04 | 3.11E+05 | 1.75E+06 | 5.10E+07 | 5.32E+07 |
| TEP | kg 1.4-DB eq | 1.41E+03 | 2.75E+03 | 2.04E+03 | 2.51E+03 | 1.41E+04 | 3.30E+06 | 3.32E+06 |
| MDP | kg Fe eq | 3.88E+05 | 8.73E+05 | 4.11E+05 | 5.82E+05 | 2.22E+06 | 5.62E+08 | 5.67E+08 |
| FDP | kg oil eq | 4.98E+06 | 1.87E+06 | 3.28E+06 | 1.61E+07 | 5.89E+07 | 6.61E+09 | 6.70E+09 |

If normalized values of impacts are taken into account (Figure 5.2), according to Europe ReCiPe Midpoint (H) method normalization factors, a comparison across impact categories becomes possible. As already pointed out in the characterization analysis, MMSW generates the greatest environmental impact in all the analyzed categories, reaching prominent values in FEP, HTP and FDP.




| | GWP | TAP | FEP | HTP | POFP | TEP | MDP | FDP |
|---|---|---|---|---|---|---|---|---|
| MMSW | 1.93E+0 | 2.31E+0 | 9.04E+0 | 7.93E+0 | 8.98E+0 | 3.99E+0 | 7.87E+0 | 4.25E+0 |
| OFMSW | 1.94E+0 | 2.72E+0 | 1.18E+0 | 3.87E+0 | 3.08E+0 | 1.71E+0 | 3.10E+0 | 3.79E+0 |
| Glass | 3.63E+0 | 5.00E+0 | 6.00E+0 | 4.97E+0 | 5.48E+0 | 3.03E+0 | 8.15E+0 | 1.04E+0 |
| Plastic | 5.47E+0 | 1.54E+0 | 4.54E+0 | 1.58E+0 | 1.17E+0 | 2.47E+0 | 5.75E+0 | 2.11E+0 |
| Metals | 5.90E+0 | 9.20E+0 | 6.83E+0 | 1.94E+0 | 4.31E+0 | 3.33E+0 | 1.22E+0 | 1.20E+0 |
| Paper | 1.54E+0 | 2.65E+0 | 4.24E+0 | 5.61E+0 | 1.54E+0 | 1.71E+0 | 5.43E+0 | 3.20E+0 |

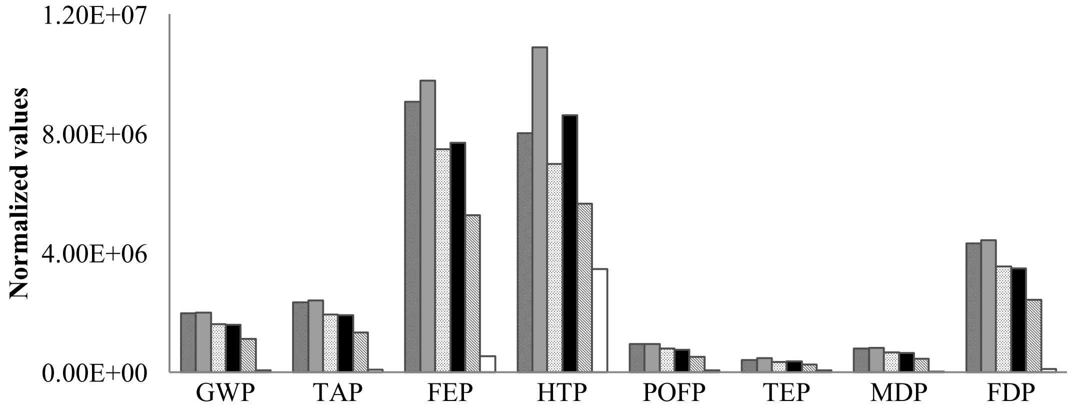
**Figure 5.2**. Recipe Midpoint (H) normalized impacts calculated for MSW management in the Metropolitan City of Naples, with reference to 1.38E9 tons of waste treated in 2012 (scenario S-$0_a$).

As expected MMSW shows the highest environmental burden, mainly due to the large amount of fraction to be managed (63% in S-0) and to the treatments to which it is subjected, landfill and WtE, notoriously very impacting (Fernández-Nava et al., 2014; Song et al., 2013). Of course, a fraction of these impacts would be abated if a better preliminary sorting is conducted, thus contributing, in a different way and extent, to the impacts of the other fractions of Figure 5.2. The management of MMSW and

OFMSW, accounts together for the largest share of MSW (up to 82%) in all impact categories. In the case of the OFMSW chain, the breakdown of the normalized impacts (not shown here) displays that the collection and transport step determines the largest share of the impacts in all categories, with treatment playing a minor role. Conversely, the treatment of mixed waste (in particular MBT) results to be the most impacting process in the MMSW chain. Taking into account these factors, alternative scenarios have been designed keeping constant the total production of MSW. As already explained, the scenarios "type a" include the increasing of recovery rate from 37% (S–0) to 50% (S–1), up to 65the (S–2), according to the Regional Urban Waste Plan and Directive 2008/98/EC, whilst scenarios "type b" assume potential treatments in the region, so as to promote the principle of proximity.

Figure 5.3 presents the normalized environmental impacts of the six different scenarios, which mainly test the potential of improving the environmental impacts by source separation and by reducing the transport distance.

The normalized impacts show that the highest normalized impacts are generated on FEP and HTP (ranging from 9.07E+06 to 5.28E+05 and from 1.09E+07 to 3.45E+06, respectively) by all analyzed scenarios. A descending trend in all impact categories is visible from S-$0_a$ to S-$2_a$: in particular, compared to S-$0_a$, scenarios S-$1_a$ and S-$2_a$ show a reduction of 13% and 30% in HTP and 18% and 42% in FEP, respectively. Therefore S-1 and S-2 result to be feasible scenarios because they imply the reduction of waste to be disposed in landfill and WtE, although no changes in the transportation routes are accomplished. Regarding the b-scenarios, S-$0_b$ and S-$1_b$ result to be more impacting than the corresponding S-$0_a$ and S-$1_a$ scenarios in all impact categories. Conversely, S-$2_b$ presents much smaller impacts compared to the corresponding S-$2_a$ scenario and, of course, in comparison to the other analyzed scenarios.




| | GWP | TAP | FEP | HTP | POFP | TEP | MDP | FDP |
|---|---|---|---|---|---|---|---|---|
| S - 0a | 1.97E+06 | 2.35E+06 | 9.07E+06 | 8.02E+06 | 9.37E+05 | 4.02E+05 | 7.93E+05 | 4.31E+06 |
| S - 0b | 2.00E+06 | 2.41E+06 | 9.78E+06 | 1.09E+07 | 9.35E+05 | 4.62E+05 | 8.19E+05 | 4.42E+06 |
| S - 1a | 1.61E+06 | 1.93E+06 | 7.47E+06 | 6.98E+06 | 7.84E+05 | 3.37E+05 | 6.50E+05 | 3.54E+06 |
| S - 1b | 1.58E+06 | 1.90E+06 | 7.69E+06 | 8.60E+06 | 7.38E+05 | 3.64E+05 | 6.46E+05 | 3.48E+06 |
| S - 2a | 1.11E+06 | 1.32E+06 | 5.27E+06 | 5.65E+06 | 5.19E+05 | 2.46E+05 | 4.49E+05 | 2.41E+06 |
| S - 2b | 6.00E+04 | 7.18E+04 | 5.28E+05 | 3.45E+06 | 6.82E+04 | 5.81E+04 | 1.52E+04 | 9.86E+04 |

**Figure 5.3.** Recipe Midpoint (H) normalized impacts calculated for the different scenarios S-$0_a$, S -$0_b$, S-$1_a$, S-$1_b$, S-$2_a$, S$2_b$

The above mentioned results can be explained by the fact that in S-$0_b$ and S-$1_b$ the amount of MMSW to be managed within the region is still high and it forces to implement new local WtE plants with specific technical characteristics, in fact it has been assumed that the new WtE plants would be similar to the one currently in operation (likely different from the ones outside the region), for which local data have been modeled and used. Furthermore, in S-$0_b$ and S-$1_b$ the need of pre-treating MMSW, still rich in organic fraction, relies on MBT plant operation. Different studies highlighted that the increased amount of organic content causes two main negative effects in MBT plants based on aerobic process: (i) increase in energy consumption as a consequence of the increased need for process air; (ii) lower stabilization level of the organic material. Conversely, in the scenario S-$2_b$, the implementation of a high quality source separation strongly reduces the need for MBT and WtE plants, resulting in a net reduction of the environmental burdens (Arena and Di Gregorio, 2014).
In agreement with previous studies, this paper further confirms that an increase in separate collection level (and the consequent decrease in the residual waste) implies an overall great improvement and benefits at both environmental and energy level (e.g. Blengini et al., 2012; Rigamonti et al., 2013). Furthermore, the contribution analysis outlined the load of transport on the total environmental impact of waste management, resulting to be one of the most sensitive parameter of the analysis. This is mainly due to the lack of local capacity-building for OFMSW treatment, being also one of the priority to be faced by the Regional Waste Management Plan.

*Conclusions*

This study confirms that MSW management is a very complex issue and LCA, if carefully conducted, allows the identification of criticalities, driving factors and improvement potentials towards new management strategies. Based on the results of the LCA carried out in this study, two crucial points can be identified as the main responsible of the environmental burdens of MSW management in the Metropolitan City of Naples: (1) the low rate of separate collection and (2) transport (in particular for organic fraction) due to the lack of regional waste treatment plants. Based on the local priorities, alternative scenarios have been envisaged: although some of the proposed scenarios do not provide optimal and final solutions within all the investigated impact categories, due to the specific technical characteristics of local plants, scenarios that are capable to increase the share of separate collection, allowing simultaneously a shorter chain in the waste processing, determine a considerable improvement of the environmental performance.

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# CHAPTER 6 – TRANSPORT MODALITIES AT URBAN AND REGIONAL LEVELS

The transportation sector is of fundamental importance when talking about sustainability. Considering the extent it supports economic and most social activities, this sector has a substantial impact on and, consequently, influence over almost all environmental matters [1]. As the second largest energy consumer sector after the industrial one, the transportation sector will account for 30% of the growth in petroleum consumption between 2004 and 2030 [2]. According to international World Energy Statistics [3], the total energy required by the global transport system worldwide rose from 23% in 1973 to 28% in 2012. In 2050, as much as 30–50% of total CO2 emissions have been predicted to come from the transportation sector [4], compared to 22% in 2008 [5]. Transportation systems have shown to be particularly quick at responding to the challenges imposed by averting global climate change [6], energy consumption and social economic development.

Terrestrial transport modalities for passengers and freight provide a large set of options and energy uses, from individual cars running on gasoline and diesel to trains and high speed trains running on electricity. Several factors affect energy use and efficiency, among which traffic, maximum load, speed, technology.
We report in this Chapter a study about transport modalities in China, performed thanks to the existing collaboration with our Chinese Partners at the Beijing Geosciences University.
We also report a study about electric bike implementation, assessed by means of the LCA approach.
Results are compared with previous studies performed in Italy, used as a benchmark per performance indicators.
Both studies apply cumulative energy efficiency, material accounting, and emergy accounting to the assessment of selected transportation options.

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This Chapter includes:

*Chapter 6.a Terrestrial transport modalities in China: a survey of monetary, energy and environmental costs.*

*Chapter 6.b Electric bike implementation.*

*Chapter 6.c Terrestrial transport modalities in Italy. A benchmark.*

# Chapter 6.a Terrestrial transport modalities in China: a survey of monetary, energy and environmental costs.

## Introduction

The transport sector in China is rapidly growing together with the economic development of this country. Specifically, the volume of the freight transport increased from 4445.2 billion ton-km in 2000 to about 17377.1 billion ton-km in 2012 and that of the passenger transport rose from 587.8 to 3338.3 billion passenger-km over the same period. The average annual growth rate was 22% and 36% for freight and passenger transport, respectively. In 2012, 84.71% and 52.89% of the total transport volume of the passenger and freight transport were delivered by the terrestrial transport because of the vast inner land area of China and relatively limited possibilities for sea transport implementation. Hence, a comprehensive and proper understanding of the terrestrial transport could be a prerequisite for the policy making and sustainable development of the transport sector.
Concerning the literature focusing on the transport sector in China, most existing studies only offer a partial picture. To be more specific, Liu et al. (2015) explore the energy consumption and $CO_2$ emissions by the passenger transport in Beijing. Xu and Lin (2015) examine the carbon dioxide emission reduction of China's freight transport via vector autoregression model. Hao et al. (2015) estimate and predict the energy consumption and greenhouse emissions by the Chinese freight transport through the year 2050. Li et al. (2016) assess the impact of the transport investment on the integrated transport system in China. Xu and Lin (2015) identify the nonlinear relationship between the influential factors (per capita GDP, energy intensity, urbanization level, cargo turnover and private vehicle inventory) of the carbon dioxide emissions of Chinese transport. Duan et al. (2015) quantify the carbon emissions of the transport sector in China by means of a streamlined life cycle assessment. Gambhir et al. (2015) evaluate the technologies and the cost of the potential reduction of carbon dioxide in the Chinese road transport sector. He and Qiu (2016) estimate the relationship between the transport harmful emissions, the environment and human health in China. Guo et al. (2014) identify the transport carbon dioxide emission patterns at regional level in China. Peng et al. (2015) uncover the energy saving and emission reduction potential of the passenger transport in Tianjin. It is evident that most of the research results about Chinese transport sector pay large attention to emissions and energy consumption, while other indirect aspects such as quality and environmental cost of resource use as well as labor intensiveness and monetary costs are not sufficiently addressed. Of course, focusing on energy is of paramount importance for the transport sector. However, infrastructure, vehicles and drivers are also important factors to operate the transport sector and all these factors should be involved into the evaluation of the resource demand and sustainability of the transport sector.

We investigate the energy, monetary and environmental costs in support to the terrestrial transport sector in china. In order to do so, we have categorized the terrestrial transport sector into 9 modalities, namely private car, taxi, urban bus, long distance bus, subway, regular train for passengers, high-speed trains, trucks and regular trains for freight transport. Monetary assessment involves total cost investment for infrastructure, vehicles, energy and labor, while energy evaluation considers the direct and indirect commercial energy consumption associated with the construction of the infrastructure and vehicles as well as the energy used to drive vehicles. Furthermore, we also implement the emergy accounting approach, which considers the direct and indirect environment support to the production and operation processes related with the transport sector at the larger scale of the biosphere. These three evaluations focus on different characteristics of the transport sector (e.g., expensive technology, energy and labor intensity, need for infrastructures, resource replacement time) and could be used for different purpose oriented policy making. Expected results are both to ascertain the monetary, energy and environmental costs per unit of transport service provided and the total costs of each modality at the level of the entire country. Moreover, the most demanding and expensive input flows are investigated, in order to suggest targeted improvements.

*Methods*

This paper compares the terrestrial transport modalities in China in terms of monetary cost and energy depletion as well as of demand for environmental support in 2012, per unit of passengers and freight transported.

*The system*

The terrestrial transport system is mainly composed by the road system, subway and railway systems. For the road system, we categorized it into different sub-modalities according to the transport purposes, namely private cars, taxi, urban buses and long distance buses, for passengers, and trucks for freight. Subway is a special sub-category, in that it only serves urban passengers as an alternative to road transport. Regular trains (electric and diesel) serve both passenger and freight transport, while high-speed trains are mainly used for passengers. Each transportation modality includes three main steps:

- Construction and maintenance of infrastructures (road, railway, bridge and tunnels);
- Construction of vehicles (cars, urban buses, long distance buses, subway trains, regular and high speed trains, trucks);
- Operation phase (annual flows of energy, labor and services).

The basic data set of all modalities were collected from the statistic yearbooks, from published official government reports and from studies carried out by international Institutions, such as the World Bank. It is quite obvious that the road system takes the dominant role in the terrestrial transportation sector in terms of the length of the infrastructure and the service supported. The total length of the road system in China is 4.24E+06 km; in the railway system, the regular railway is 9.67E+05 km and the high-speed railway is 1.01E+04 km. The road system transported 5.76E+12 P-km in 2012 that accounts for 84% of total transport service by all terrestrial transport modalities, while the railway and subway systems transport 14% and 2% of the total transport service, respectively. Among the road transport modalities, private cars and long distance buses are the two most important ones and respectively provide a transport service around 3.01E+12 p-km (44% of the total) and 1.85E+12 p-km (27% to the total). (Table 6.1)

**Table 6.1.** Infrastructures, vehicles and services supporting terrestrial transportation in China (2012)

| Item | | Amount | Unit |
|---|---|---|---|
| **Infrastructure** | | | |
| **Road system** | | | |
| | *Extra urban road* | | |
| | Length | 4.24E+09 | m |
| | Area | 3.69E+10 | $m^2$ |
| | *Internal urban road* | | |
| | Length | 3.11E+06 | m |
| | Area | 7.50E+10 | $m^2$ |
| **Train system** | | | |
| | Regular railway | 9.67E+08 | m |
| | High-speed railway | 1.01E+07 | m |
| | Subway | | |
| | Railway | 2.06E+06 | m |
| **Vehicles** | | | |
| **Road system** | | | |
| | Private cars | 8.84E+07 | Item |
| | Urban buses | 4.19E+05 | Item |
| | Taxi | 1.03E+06 | Item |
| | Long distance buses | 8.67E+05 | Item |
| | Trucks | 1.25E+07 | Item |
| **Train system** | | | |
| | *Regular train (for passengers)* | | |
| | Coaches | 5.58E+04 | Item |
| | Locomotives | 3.25E+03 | Item |
| | *Regular train (for freight)* | | |
| | Coaches | 6.64E+05 | Item |
| | Locomotives | 1.64E+04 | Item |
| | High-speed train | 1.05E+03 | Item |
| **Subway** | | | |
| | Trains | 1.26E+04 | Item |
| **Transportation service provided** | | | |
| **Road system** | | | |
| | Private cars | 3.01E+12 | P-km |
| | Urban buses | 7.01E+11 | P-km |
| | Taxi | 2.10E+11 | P-km |
| | Long distance buses | 1.85E+12 | P-km |
| | Trucks | 5.95E+12 | Ton-km |
| **Train system** | | | |
| | Regular train (passenger) | 5.35E+11 | P-km |
| | Regular train (freight) | 2.69E+12 | Ton-km |
| | High-speed train | 4.43E+11 | P-km |
| | Subway trains | 1.15E+11 | P-km |

*Accounting methods*

We treated each transport modality as an independent system (disregarding, as comoaratively negligible, the specific infrastructures that connect each modality to the others) and firstly carried out a thorough inventory of all the input flows on the local scale (foreground data). It is important to underline that this inventory forms the common basis for all subsequent assessments, namely monetary cost accounting, gross energy requirement and emergy accounting, which are carried out in parallel, thus ensuring the maximum consistency of the input data and inherent assumptions.

The raw amounts of input flows from the inventory phase are multiplied by suitable conversion coefficients specific of each method applied, which express the “intensity” of the flow, i.e. quantify to what extent a monetary, energy, or environmental cost is directly or indirectly associated to background flows over its whole life cycle. Such coefficients are available in published statistic yearbooks, energy and environmental accounting literature (emergy, LCA). In so doing, the background monetary, energy, and environmental “costs” associated to each flow are calculated, according to the following generic equation:

$$C = \sum C_i = \sum f_i \times c_i \quad i = 1, \cdots, n, \qquad (1)$$

where $C$ = monetary, energy or environmental cost associated to the investigated process; $C_i$ = monetary, energy or environmental cost associated to the $i$-th inflow of matter or energy; $f_i$ = raw amount of the -$i$th flow of matter or energy; $c_i$ = moneraty, energy or environmental unit cost coefficient of the $i$-th flow (from literature or calculated in this work).

In order to carry out a reliable comparison of the different modalities, we referred all costs and impacts to one person or 1 tonne of commodity transported over one km, i.e. to functional units typical of transportation systems. The choice of such a functional unit seems the only one that allows a fair comparison of so different transportation modalities by means of so different evaluation methods. In so doing, the comparison can be drawn independently on the distance as well as on the actual volume of people transported. We therefore calculated the average demand for resources and environmental support related to such p-km and t-km functional units. By means of a whole-system approach, we were able to calculate and compare the monetary and energy depletion required as well as the environmental impact generated per functional unit of each analysed transport system, taking into account all the system’s steps and components, not just the specific performance of individual vehicles, out of their operational context.

*Monetary cost accounting*

Monetary cost accounting includes the total cost of the infrastructure, vehicle, fuel and the salary paid for the employees to operate each transportation modality. According to equation (1), the calculation of the monetary cost of the each transport modality needs the amount of the input flows be multiplied by the unit cost of each flow in monetary term. However, there is a small difference in the procedure, namely that the input flows, especially for infrastructure and vehicles, are not measured in mass terms but according to length or number of items. For instance, the road/railway is accounted in terms of its length and multiplied by the monetary cost per unit length (from technical handbooks), in order to yield the total cost invested in the road/ railway construction. In conducting a similar procedure also for vehicles, human labor and energy used (generally expressed as kwh or TCE, ton coal equivalent), we finally ascertain the total monetary cost of each transport modality.
The unit price is the unit cost coefficient of one input flow in monetary term. Prices also include a tax component, that is larger for cars and fuels. And the tax revenue from such goods is both a way to affect choices, by making those goods more expensive and convincing people not to use them, and a way to easily collect money from the most used modalities in order to support infrastructures and other investments. In general Governments tax what is largely used or what needs to be limited (fuels for private cars, cigarettes, luxury goods), not the electricity supporting trains and subway. Hence, we assess the monetary cost of each modality with and without tax.

*Energy accounting*

According to the International Federation of Institutes for Advanced Study (IFIAS, 1974), energy analysis has been defined as the process of determining the energy required directly and indirectly to allow a system to produce a good or service. The IFIAS conventions were mainly aimed at quantifying the availability and use of fossil fuels stocks (also referred to as "commercial energy" and named G.E.R., Gross Energy Requirement). G.E.R. accounts for the amount of fossil energy that is required directly and indirectly by the process of making a good or service. More specifically, it focuses on fuels and electricity, fertilizers and other chemicals, machinery, and assets supplied to a process in terms of the direct and indirect fossil energy required to produce and make them available to the process (Slesser, 1978; Smil, 1991). Later on, the Cumulative Energy Demand (C.E.D.) method was developed as a refinement of G.E.R., within a Life Cycle Perspective. In addition to accounting for LCA background energy input flows, C.E.D. generally quantifies the total energy demand broken down into its renewable and nonrenewable components. However, the renewable energy flows in C.E.D. are only those captured through technological devices, disregarding those flows that are directly supplied through natural patterns (e.g. photovoltaic electricity is included, but the solar radiation supporting photosynthesis is not). As a consequence, the C.E.D. of a product or a functional unit is mainly concerned with the depletion of fossil energy, that is the largest fraction in almost all cases. In this study, the C.E.D. method was chosen to specifically address

the total consumption of direct and indirect energy for infrastructure, vehicles and operations of each transport modality, converting, expressed in fossil-equivalent energy units per physical unit of good or service provided (for instance, MJ per kg of steel).
The C.E.D. of the i-th input to the investigated process was calculated by multiplying the raw amount of that input by its energy intensity factor (this is, generally, achieved by using commercial LCA software, but databases also exist to perform such calculation without software use), according to Equation (1). Then, the total C.E.D. cost of the whole process was calculated as the sum of the Cumulative Energy Demand of all input flows. Finally, the C.E.D. of the product was expressed as the total amount of fossil energy required per P-km or Ton-km.

*Emergy accounting*

The Emergy Accounting (Odum, 1988, 1996; Brown and Ulgiati, 2004) is an energy evaluation method rooted in irreversible thermodynamics and systems thinking. The method is aimed at evaluating the environmental performance of the system on the global scale of biosphere, also taking into account free environmental inputs (e.g., solar radiation, wind, rain, and geothermal flows) as well as indirect environmental support embodied in human labor and services (Franzese et al., 2009). Emergy Accounting is a measure of the cumulative environmental support to a process, and it allows exploring the interplay of natural ecosystem and human activities. According to this method, all inputs are accounted for in terms of their solar emergy, defined as the total amount of solar available energy (exergy) directly or indirectly required to make a given product or support a given flow, and measured as solar equivalent joules (seJ).
The amount of emergy that is required to generate one unit of each input is referred to as its specific emergy in the case of mass flows (sej/g) and solar transformity in the case of energy flows (sej/J). Emergy intensity factors can be considered "quality" factors accounting for the environmental support provided by the biosphere to the formation of each input. They are sometimes also referred to as UEV (Unit Emergy Values).
Raw data on mass, energy, labor, and money flows were converted into emergy units and then summed into a total amount of emergy used by the system, according to Equation (1).

*Allocation*

Roads and railways support both passenger and freight transport. Therefore, the infrastructure costs need to be assigned to both kind of transport, in proportion to some measure of use. A choice about allocation methods should involve firstly the relative amount of traffic supported. Although different allocation procedures could have been chosen, we decided to allocate all infrastructural costs linearly according to the total weight of vehicles (mass of vehicle plus mass of passengers or commodities) that use

such infrastructures. Our choice is based on the evidence that, a part from weathering, degradation of infrastructure over time is mainly related to the pressure of use, which we assumed to be linearly proportional to the weight of the vehicles. We applied the same rationale to the degradation of vehicles. In order to compare passengers and freight transport and allocate infrastructure and maintenance input accordingly, an average passenger weight of 65 kg was assumed.
We also allocate the cost of the infrastructure and vehicle according to their life span to get the annual cost for all modalities.

*Results*

Table 6.1 provides monetary, energy and emergy values of input flows supporting selected investigated modalities. Due to the limit space we just display the evaluation results for private cars, regular trains and high-speed trains for passenger transport. Results from the evaluation of other modalities are summarized in Tables 6.5 to Table 6.7.

*Monetary results.*

Money flows only refer to the monetary costs of fuels, vehicles, direct and indirect labor, as well as infrastructures. The totality of the monetary cost of 9 terrestrial transport modalities is 5.77E+12 YUAN, and private car and trucks accounts 40.9% and 37.3% of the totality, respectively. For the total annual cost of private cars and trucks, the cost invested in the infrastructure construction present the highest share and reach 44% and 58%. The private car and trucks have the highest flexible and are capable of transporting passengers or commodities from door to door, which is supposed to be based on a developed and sophisticated road system. However, the usage intensities of different roads in the system could be different. The roads connecting with the key road junctions could be used more frequently compared with the road in the countryside. All roads with different usage intensities are necessary to support the car system and cost huge. Lowering the cost of the infrastructure construction may be achieved by using better technology or by using materials and designs that make the road last longer.
We also assigned a (virtual) monetary cost to the labor of non professional drivers of private cars, since the driving time to and from work place or to reach any other location of interest, might have been used to perform paid work. If driving times are shortened, by favoring decreased distances between living, working and leisure sites, more time would be available for work and rest, the monetary value of which cannot be denied. And the total monetary cost assigned to the drivers of private cars accounts 25% of the totality of the monetary cost invested to the private car modality. Even though we eliminate the share of the assumed labor cost, the dominating place of the private cars among all modalities in the total monetary cost doesn’t change.
Concerning the unit monetary cost (cost of p-km or ton-km), the taxi and private car rank in the topping places among all 9 modalities and cost 0.85Yuan/p-km and 0.79

Yuan/p-km, respectively. Meanwhile, the lowest unit cost is achieve by the regular trains (0.04 Yuan/p-km) and the high-speed train (0.07 Yuan/p-km) for passengers, The unit cost of the private car and taxi are double of that of trucks and even greater than other modalities, which means the same amount of the monetary investment in different modalities will offer different volume of services. For instance, the service offered by each modality could be various with the same amount investment. Specifically, the private car and regular train will offer 126.8 p-km and 2500 p-km with 100 Yuan investment, respectively. (Table 6.2)

**Table 6.2.** Monetary evaluation of private cars, regular train and high-speed trains (passengers) transport in China (2012).

| Note | Item | Amount | | | Unit/yr |
|---|---|---|---|---|---|
| | | Private car | Regular train | High-speed train | |
| 1 | Oil derived fuels | 6.03E+11 | 3.79E+09 | | RMB |
| 1a | Without tax | 3.24E+11 | 2.04E+09 | | RMB |
| 1b | Tax | 2.78E+11 | 1.75E+09 | | RMB |
| 2 | Natural gas/electricity | 5.07E+09 | 2.15E+09 | 7.67E+09 | RMB |
| 2a | Without tax | 4.10E+09 | 1.78E+09 | 6.36E+09 | RMB |
| 2b | Tax | 9.62E+08 | 3.65E+08 | 1.30E+09 | RMB |
| 3 | Infrastructure | 1.03E+12 | 1.19E+10 | 1.19E+10 | RMB |
| 4 | Vehicles | 1.33E+11 | 1.31E+09 | 6.72E+09 | RMB |
| | Without tax | 9.94E+10 | | | RMB |
| | Tax | 3.31E+10 | | | RMB |
| 5 | Drivers labor | 5.97E+11 | 1.64E+09 | 6.65E+09 | RMB |
| | **Total with tax** | 2.36E+12 | 1.91E+10 | 3.30E+10 | RMB |
| | **Total without tax** | 2.05E+12 | 1.67E+10 | 3.17E+10 | RMB |
| | **Total transportation service provided** | 3.01E+12 | 5.35E+11 | 4.43E+11 | P-km |
| | **Cost of unit of service with tax** | 0.79 | 0.04 | 0.07 | RMB/p-km |
| | **Cost of unit of service without tax** | 0.68 | 0.03 | 0.07 | RMB/p-km |

*Energy results.*

Results express the cumulative expenditure of energy, mainly fossil fuels (liquid fuels and nature gas for cars; coal for electric vehicles) and the contribution of transport to fossil depletion (and, indirectly, to $CO_2$ emissions and climate change). Table 6.3 expresses the dependence of transportation on (fossil) energy supply directly (consumption by engines) and indirectly (industrial consumption over the supply chain).

Private cars and trucks consume 66% of total 1.24E+13 MJ cumulative energy of all modalities, which means that these two modalities play a dominant role in the energy depletion and must be monitored for much needed improvement. The cumulative energy consumption structure is not the same for all modalities and could be categorized into two groups. The first group including regular trains for passengers

and freight of which the cumulative energy of the supporting infrastructure is around 65% and 76%, respectively. In the second group (including all the remaining modalities), the largest fraction of the total cumulative energy consumption is the fuel and electricity used to drive vehicles and accounts between 74% to 84% of the total.
Come to the cumulative energy consumption per service, taxi and the private car consume 2.06E+10 Mj and 1.74 E+10 Mj to transport 1 p-km, respectively and are much higher than other modalities. The cumulative energy consumption of taxi is higher than the private car is mainly due to that the taxi offers less service than the private car. Hence, an easier approach to improve the energy efficiency for the taxi modality is to shift the private car drivers and passengers to the taxi. In contrast, subway and the high speed train just cost 0.21 E+10 MJ and 0.47 E+10 MJ direct and indirect energy to offer one unit of service, which means that the subway and high speed trains are the most efficient modalities among all terrestrial modalities and they could offer more service with given energy consumption. (Table 6.3)

**Table 6.3.** Cumulative Energy Demand evaluation of private car, regular train and high-speed train (passenger) transport in China (2012).

| | | **Raw Amount** | | | | | **Energy (E10 MJ/yr)** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Note** | **Item** | **Private car** | **Regular train (Passengers)** | **High-speed train** | **Unit/yr** | **Energy intensity (MJ/unit)[21]** | **Private car** | **Regular train (Passengers)** | **High-speed train** |
| **FUELS** | | | | | | | | | |
| 1 | Oil derived fuel | 8.11E+13 | 5.80E+11 | | g | 5.40E-02 | 4.38E+02 | 3.13E+00 | |
| 2 | Natural gas | 1.44E+12 | | | g | 1.20E-01 | 1.73E+01 | | |
| 3 | Electricity | | 3.58E+09 | 1.28E+10 | kwh | 1.50E+01 | | 5.37E+00 | 1.92E+01 |
| **VEHICLES** | | | | | | | | | |
| 3 | Vehicles | 7.64E+12 | 2.16E+11 | 2.78E+13 | g | 6.93E-02 | 5.29E+01 | 4.70E+00 | 2.34E-01 |
| 4 | Locomotives | | 2.12E+11 | | | | | 2.11E+00 | |
| **INFRASTRUCTURE** | | | | | | | | | |
| 4 | Road/Railway | 1.14E+15 | 9.38E+13 | 1.20E+12 | | 1.20E-04 | 1.38E+01 | 2.41E+01 | 1.23E+00 |
| **Total transportation service provided** | | 3.01E+12 | 5.35E+11 | 4.43E+11 | P-km | | | | |
| **Total energy** | | 5.22E+02 | 3.74E+01 | 2.06E+01 | MJ | | | | |
| **Cumulative energy per service** | | 1.74 | 0.70 | 0.47 | MJ/p-k | | | | |

*EMergy results.*

Emergy provides a much broader point of view and sustainability assessment because its accounting procedure also includes:

a) the direct ecosystem services provided for free by nature (sun, rain and wind, among others);

[21] The energy density of the vehicles and infrastructure is materials, weighted average energy density

b) the environmental support to the larger infrastructures of the economy needed for the transport sector to function (governmental, protection, commerce, etc);
c) the indirect labor and know-how over the supply chain as well as the direct labor applied to the process, when running;
d) the embodied time and biosphere work in support of resource generation.

It is evident that, while monetary and energy points of view are more feasibility and efficiency oriented, in terms of direct availability and appropriate use of money and energy resources, the emergy method is more sustainability oriented, in terms of global view and interplay with biosphere dynamics and resource replacement ability.

In this study, we calculate the total emergy with and without Labor and Services, as well as the total emergy with and without taxes. As said earlier, taxes are levied with the twofold aim of limiting the use of a resource and of collecting money to support other sectors (e.g., education, health, environmental protection), in addition to the transport itself. The total emergy with labor and service involves emergy of all factors to operate each transport modality, namely renewable resources, fuels, vehicles, infrastructure and labor and services. All of them are needed for the operation of transport services. Lack of any of these factors would make impossible to run the transport sector. We also calculate the total emergy without labor and service only to demonstrate to what extent the larger societal system affects the individual process (according to Odum's claim that the local scale can only be fully understood if we look at it from the next larger scale). In a like manner as for the monetary assessment, the total emergy calculated without including taxes quantifies the resource investment directly related with the transport, while the total emergy with taxes also includes the emergy of societal support other than the indirect labor and know-how associated to the transport supply chain.

Table 6.4 displays the emergy evaluation results of the private car, regular train and high-speed train. The total emergy with labor and service used by the terrestrial transport modality is 6.42E+24 sej/yr, of which private cars and trucks account 72% (36% for each). For the dominant modalities of private cars and trucks, the emergy of the labor and service reach 77% and 79%, which means that these two modalities are labor intensive. Therefore, the development of the trucks transport could offer more jobs; the labor and time used by driving private car actually do not be paid and if transport these private drivers could save more time to relax and work. We also consider the total emergy without the labor and service that could display the demand of the natural resource of the transport sector. The total emergy without the labor and service of all modalities is 1.82E+24 sej/yr. The private car and the truck are still the dominant modalities and account 29% and 26%.

The emergy used by per service reflect the efficiency of using the resource and labor of each modality, the private car and taxi has the highest UEV per service among all passenger transport modalities and reach 7.65E+11 sej/p-km and 7.47E+11 sej/p-km, respectively. For the commodity transport, the trucks modality need 3.36E+11 sej/ton-km and is at least twice higher than the regular train.

**Table 6.4.** Emergy evaluation of private car, regular train and high-speed train (passenger) transport in China (2012).

| Note | Item | Raw Amount | | | Unit/yr | UEV (sej/unit) (*) | Solar Emergy (E18 sej/yr) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Private car | Regular train | High-speed train | | | Private car | Regular train | High-speed train |
| **RENEWABLE RESOURCES:** | | | | | | | | | |
| 1 | Sunlight | 2.43E+20 | 8.29E+20 | 5.22E+16 | J | 1 | 2.43E+02 | 8.29E+02 | 5.22E+01 |
| 2 | Rain | 8.04E+14 | 2.74E+15 | 1.73E+11 | J | 2.13E+04 | 1.71E+01 | 5.84E+01 | 3.68E+00 |
| 3 | Wind | 5.42E+17 | 1.85E+18 | 1.17E+14 | J | 1.00E+03 | 5.42E+02 | 1.85E+03 | 1.17E+02 |
| 4 | Geothermal heat | 1.34E+17 | 4.57E+17 | 2.88E+13 | J | 4.90E+03 | 6.56E+02 | 2.24E+03 | 1.41E+02 |
| **FUELS** | | | | | | | | | |
| 5 | Oil derived fuel used by private cars | 3.65E+18 | 2.67E+14 | | J | 1.32E+05 | 4.82E+05 | 5.79E+09 | |
| 6 | Natural gas used by private cars | 2.01E+17 | | | J | 1.40E+05 | | | |
| 7 | Electricity | | 1.29E+17 | 4.60E+17 | J | | 2.82E+04 | 3.54E+05 | 1.63E+08 |
| **VEHICLES** | | | | | | | | | |
| 8 | Vehicle | 7.64E+12 | 2.16E+11 | 2.78E+10 | g | 1.92E+09 | 1.47E+04 | 2.41E+03 | 383859.55 |
| 9 | Locomotives | | 6.27E+09 | | g | | | 1.68E+02 | |
| **INFRASTRUCTURE** | | | | | | | | | |
| 10 | Roads system | 1.14E+15 | 1.38E+05 | 1.19E+12 | g | | 3.24E+03 | 5.79E+09 | 21835.83 |
| **LABOUR & SERVICE** | | | | | | | | | |
| 11 | Services for oil derived fuels | 6.03E+11 | 3.79E+09 | | RMB | 8.61E+11 | 5.19E+05 | 3.27E+03 | |
| 11a | without tax | 3.24E+11 | 2.04E+09 | | RMB | 8.61E+11 | 2.79E+05 | 1.76E+03 | |
| 11b | tax | 2.78E+11 | 1.75E+09 | | RMB | 8.61E+11 | 2.40E+05 | 1.51E+03 | |
| 12 | Services for natural gas/electricity | 5.07E+09 | 2.15E+09 | 7.67E+09 | RMB | 8.61E+11 | 4.36E+03 | 1.85E+03 | 6.60E+03 |
| 12a | without tax | 4.10E+09 | 1.78E+09 | 6.36E+09 | RMB | 8.61E+11 | 3.53E+03 | 1.54E+03 | 5.48E+03 |
| 12b | tax | 9.62E+08 | 3.65E+08 | 1.30E+09 | RMB | 8.61E+11 | 8.29E+02 | 3.14E+02 | 1.12E+03 |
| 13 | Services for roads | 1.03E+12 | 1.19E+10 | 1.19E+10 | RMB | 8.61E+11 | 8.83E+05 | 1.03E+04 | 1.03E+04 |
| 14 | Services for vehicle | 1.33E+11 | 1.31E+09 | 6.72E+09 | RMB | 8.61E+11 | 1.14E+05 | 1.13E+03 | 5.79E+03 |
| 14a | without tax | 9.94E+10 | | | RMB | 8.61E+11 | 8.56E+04 | | |
| 14b | with tax | 3.31E+10 | | | RMB | 8.61E+11 | 2.85E+04 | | |
| 15 | Drivers labor | 1.12E+07 | 3.08E+04 | 1.25E+05 | Person-yr | 2.21E+16 | 2.47E+05 | 6.80E+02 | 2.75E+03 |

| | | | | | |
|---|---|---|---|---|---|
| Total transportation service provided | 3.01E+12 | 5.35E+11 | 4.43E+11 | p-km | |
| **Total emergy (with L&S)** | | | 2.30E+06 | 3.47E+05 | 1.63E+08 |
| **Total emergy (without L&S)** | | | 5.30E+05 | 3.30E+05 | 1.63E+08 |
| **Total emergy (without tax)** | | | 2.03E+06 | 3.42E+05 | 1.63E+08 |
| **UEV of transportation service (sej/p-km), with L&S** | | | 7.65E+11 | 6.48E+11 | 3.68E+11 |
| **UEV of transportation service (sej/p-km), without L&S** | | | 1.76E+11 | 6.16E+11 | 3.68E+11 |
| **UEV of transportation service (sej/p-km), without labor of drivers** | | | 6.82E+11 | 6.47E+11 | 3.68E+11 |
| **UEV of transportation service (sej/p-km), without tax** | | | 6.75E+11 | 6.39E+11 | 3.68E+11 |

*Summary of results*

Based on the evaluation results, we may rank all transport modalities based on their unit cost per P-km or Ton-Km. The ranking is different according to the various evaluation manners. In terms of energy, we may consider (and compare) the direct energy consumption that is used to drive the vehicles and the gross energy requirement that also includes the energy used to construct the infrastructure and the vehicles as well as to process the raw fossil fuels to a usable form. Concerning the ranking in direct energy terms, the private car is the most energy-intensive modality, closely followed by the taxi (Table 6.5). The public transportation and railway modalities are much more energy efficient, with much lower energy intensities per unit of service. The two ways of ranking, direct and gross energy requirement based, show an expected increase of energy intensity when the gross energy requirement is considered. Interesting is the relatively low increase of the road system (between 25 and 100%) compared with the large increase of the railway systems (subway to high-speed) ranging between 4 and 10 times. The two results (lower energy intensity and dominance of infrastructure and technology costs in railway) indicate that investing in railway technology and vehicles requires a larger start-up energy cost that is rewarded over time by a much lower energy cost per unit of service performed.

For freight transport, the regular train modality consumes less energy than other modalities, even with consideration of the indirect energy used for the railway and vehicles.

There is an underlying assumption in our private car ranking. Private cars intensively use the roads in cities, counties, and towns, while village roads are used by a lower extent. Our calculations are performed with and without including these village roads, characterized by less intensity of use. If village roads are not included, values may slightly change because the energy for construction as well as their use by a smaller number of users are not accounted for. Hence, the private car assessment without including the village roads (i.e., their energy cost and use) shows a slightly lower C.E.D. ranking compared with the "all road" assessment. C.E.D. also affects the ranking of regular and high-speed trains.

The picture provided by the emergy ranking, with and without inclusion the emergy supporting labor and services, is totally different (Table 6.6). The private car and taxi modalities are labor-intensive, which leads to high ranking of their UEVs with L&S,

followed by the high speed train. Instead, if L&S are not included, the ranking places trains in the first positions, with unexpected higher intensity for regular passenger trains than high speed trains. This result, very different than in the energy ranking, points out the huge contribution of materials for vehicles and infrastructure as well as the highe energy efficiency (less energy cost per unit of service). The urban bus is always the last one in the emergy ranking, that can be likely attributed to the very intensive use of this modality for short distances, due to its coverage of the urban area and cheap price.

Trucks show a much lower demand for environmental support when evaluated without L&S. Inclusion of materials for railway vehicles and infrastructure pushed trains to the first position, while the opposite was true when only energy was considered. However, L&S inclusion makes trucks again less competitive than trains in environmental terms.

**Table 6.5.** The energy ranking of transport modality.

| No. | Modality | Direct energy consumption (MJ/p-km) | Modality | Cumulative Energy Demand (MJ/p-km) |
|---|---|---|---|---|
| Passenger transport | | | | |
| 1 | Private car | 1.28 | Taxi | 2.05 |
| 2 | Private car without village roads | 1.28 | Private car | 1.74 |
| 3 | Taxi | 1.18 | Private car without village roads | 1.70 |
| 4 | Long distance bus | 0.54 | Long distance bus | 0.87 |
| 5 | Urban bus | 0.25 | Urban bus | 0.72 |
| 6 | High speed train | 0.10 | Regular trains | 0.7 |
| 7 | Regular trains | 0.07 | High speed train | 0.47 |
| 8 | Subway | 0.05 | Subway | 0.21 |
| Commodity transport | | | | |
| 1 | Trucks | 0.61 | Trucks | 0.76 |
| 2 | Regular trains | 0.07 | Regular trains | 0.71 |

**Table 6.6.** The emergy ranking of transport modality

| No. | Passenger transport | UEV with L&S (sej/p-km) | Passenger transport | UEV without L&S (sej/p-km) |
|---|---|---|---|---|
| 1 | Private car | 8.56E+11 | Regular trains | 3.69E+11 |
| 2 | Taxi | 7.66E+11 | High speed train | 3.68E+11 |
| 3 | Private car without village roads | 6.07E+11 | Long distance bus | 3.52E+11 |
| 4 | High speed train | 4.26E+11 | Taxi | 2.24E+11 |
| 5 | Regular trains | 4.01E+11 | Private car | 1.76E+11 |
| 6 | Long distance bus | 3.54E+11 | Private car without village roads | 1.75E+11 |
| 7 | Subway | 3.45E+11 | Subway | 1.59E+11 |
| 8 | Urban bus | 2.32E+11 | Urban bus | 5.55E+10 |

| | Commodity transport | UEV with L&S (sej/T-km) | Commodity transport | UEV without L&S (sej/T-km) |
|---|---|---|---|---|
| 1 | Trucks | 4.40E+11 | Regular trains | 1.57E+11 |
| 2 | Regular trains | 1.71E+11 | Trucks | 8.09E+10 |

The monetary ranking with and without the inclusion of levied taxes is exactly the same. Of course, the absolute values change, indicating that the monetary cost of the road system (except for urban buses) is much higher than for the subway and train systems. Especially, the exclusive feature of the private car and taxi lead to extremely high economic costs. (Table 6.7)

**Table 6.7.** The monetary ranking of transport modality

| No. | Passenger transport | Cost of unit of service with tax (RMB/p-km) | Passenger transport | Cost of unit of service without tax (RMB/p-km) |
|---|---|---|---|---|
| 1 | Taxi | 0.85 | Taxi | 0.68 |
| 2 | Private car | 0.79 | Private car | 0.71 |
| 3 | Private car without village roads | 0.57 | Private car without village roads | 0.46 |
| 4 | Long distance bus | 0.39 | Long distance bus | 0.34 |
| 5 | Subway | 0.24 | Subway | 0.24 |
| 6 | Urban bus | 0.17 | Urban bus | 0.14 |
| 7 | High speed train | 0.07 | High speed train | 0.07 |
| 8 | Regular trains | 0.04 | Regular trains | 0.03 |
| | Commodity transport | | | |
| 1 | Trucks | 0.43 | Trucks | 0.37 |
| 2 | Regular trains | 0.11 | Regular trains | 0.10 |

*Discussion*

The total annual final energy consumption in China is 1.84E+9 tonnes of oil equivalent and the transport sector accounts 13% of the totality (Table 6.8). The final energy consumption of the transport is 2.39E+8 tonnes of oil equivalent equal to 1.02E+19 J (92% is oil products), 32% smaller than the cumulative energy consumption of the transport sector (1.48 E+19 J), which is because the cumulative energy demand not only includes the direct energy consumed by the transport sector but also includes the indirect energy used to produce the vehicles, build the infrastructure and process the fuel. Most of the indirect energy is belonging to the industrial sector, which leads to the difference between the final energy consumption and the cumulative energy consumption of the transport sector.

Compared with the share of the final energy consumption, the contribution of the transport sector to GDP in 2012 is only 5% (Table 6.9). Transport sector has much lower energy efficiency than the industry that consumes 51% of the total final energy demand and reach 38% of the total GDP. Hence, it is important to improve the energy efficiency of the transport sectors.

*Integrating different perspectives, frameworks and boundaries.*

The total monetary, energy and emergy costs of terrestrial transportation sector in China in 2012 are 5.77E+12 RMB, 1.48E+19 J and 7.37E+24 sej, respectively, and these costs are 11.18%, 11.94% and 25.15% of total GDP, energy budget and emergy use in China (Bo Lou and Ulgiati, 2013). (Table 6.10)

**Table 6.8**. Final consumption of sectors in China in 2012 (*)

| | Coal | crude oil | oil products | natural gas | Nuclear | hydrogen | Geothermal, solar, etc. | Biofuels and waste | electricity | Heat | total | percentage |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total final consumption** | **707220** | **1045** | **407281** | **83161** | **0** | **0** | **17021** | **198700** | **355017** | **71877** | **1841322** | **100%** |
| Industry | 559585 | 560 | 50885 | 29883 | 0 | 0 | 175 | 0 | 240273 | 49500 | 930861 | 51% |
| Transport | 3099 | 0 | 218985 | 10343 | 0 | 0 | 0 | 1732 | 4470 | 0 | 238629 | 13% |
| Residential | 50158 | | 24805 | 24118 | 0 | 0 | 13795 | 196967 | 53483 | 18533 | 381859 | 21% |
| Commercial and public services | 19532 | 0 | 15263 | 7407 | 0 | 0 | 2486 | 0 | 21006 | 1700 | 67394 | 4% |
| Agriculture/forestry | 11867 | 0 | 15718 | 54 | 0 | 0 | 535 | 0 | 8708 | 27 | 36909 | 2% |
| Fishing | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2116 | 2116 | 0% |
| Non-specified | 19695 | 121 | 0 | 9 | 0 | 0 | 30 | 0 | 27076 | | 46931 | 3% |
| Non-energy use | 43284 | 364 | 81624 | 11356 | 0 | 0 | 0 | 0 | 0 | | 136628 | 7% |
| -of which chemical/petrochemical | 0 | 364 | 49638 | 11356 | 0 | 0 | 0 | 0 | 0 | | 61358 | 3% |

(*) thousand tonnes of oil equivalent (ktoe) on a net calorific value basis

**Table 6.9.** The GDP contribution of sectors in 2012

| Sectors | Amount (Yuan) | Percentage(%) |
|---|---|---|
| **Total** | 5.19E+15 | 100% |
| **Primary Industry** | 5.24E+14 | 10% |
| Agriculture, Forestry, Animal Husbandry and Fishery | 5.24E+14 | 10% |
| **Secondary Industry** | 2.35E+15 | 45% |
| Industry | 2.00E+15 | 38% |
| Construction | 3.55E+14 | 7% |
| **Tertiary Industry** | 2.32E+15 | 45% |
| Transport, Storage and Post | 2.47E+14 | 5% |

The three methods (monetary, energy and emergy assessments) capture different aspects that are all mandatorily needed for improvement policies. Results are different in their details, as shown in Tables 6.5, 6.6 and 6.7, in that the different methods are designed to focus on specific aspects and disregard, by definition, other characteristics of the investigated systems. A full understanding cannot be based on one approach only, nor a sustainable and reliable transport policy can be based only on monodimensional understanding. Money captures, by definition, the market dynamics, the willingness to pay in time and space due to the negotiation of demand and offer. Monetary indicators are crucial for feasibility decision-making, in that money is related to direct and indirect purchase of labor time. However, money is a very unstable measure of value, affected by geo-political strategies and conditions, and – although capable to dominate the short-time decision – it does not provide any long-time sustainability reference. The energy approach captures the relation of the economic process with the amount of commercial energy that is available. Production and consumption processes are constrained and limited by the ability to exploit energy resources efficiently and effectively. As H.T. Odum used to say, "A tank of gasoline drives a car the same distance regardless of what people are willing to pay for it" (Odum, 1994). Therefore, the energy approach only looks at the heat quantity and its goal is to expand the resource basis. Policies about commercial energy aim at acquiring cheap energy from abroad, to integrate local availability. Understanding the energy intensities of products and services allows, in specific cases, to increase the use efficiency, in order to do more with less. The emergy perspective is to understand and balance the interplay of human dominated patterns and the environment as a source and a sink of resources. This applies not just to energy resources, but also to material resources, the value of which is assessed in terms of production time by natural mechanisms. The emergy approach captures the value of ecosystem services in terms of renewable emergy flows, the biosphere work in the past generation of fossil fuels and minerals, the resource investment embodied in supporting labor and services (i.e. food, fuels, house, transport, education).

**Table 6.10.** The percentage of terrestrial transport of the totality of China in Monetary, energy and emergy terms

| | Monetary (Rmb/yr) | Cumulative energy demand (J/yr) | Emergy (sej) |
|---|---|---|---|
| Totality of the transport | 5.77E+12 | 1.48E+19 | 7.37E+24 |
| Totality of China | 5.16E+13 | 1.24E+20 | 2.93E+25 |
| Percentage (%) | 11.18% | 11.94% | 25.15% |

*Policy making*

Monetary results highlight that the road system cost more (per unit of service provided) than the railway system, especially private car and taxi modalities. The private car and taxi cost more because of their exclusiveness and lower transport efficiency. Moreover, they are loaded by governmental tax policies to collect easy money for investments as well as to control the growth of the number of private cars. Taxes on fuel use for commodity transport might also increase the cost of food and other transported items, which may heavily affect the public well-being. As a consequence, several authors suggested not to tax resources, but instead tax their misuse by inaccurate users (Slesser, 1989; Odum, 1996; Bimonte and Ulgiati, 2002, among others). On the other end, taxes on fuels may push people towards mass transport or electric vehicles, thus decreasing pollution within cities. Monetary costs are most often also related to construction and maintenance of transport infrastructures, the cost of which may become overwhelming if not allocated to a large number of user over a long discounting time.

Energy results suggest that private vehicle modalities are more energy dependent than others. As a consequence of energy results, conservation policies should be implemented:

a) The mass transport is generally more energy efficient than individual cars and is supposed to be promoted.
b) Even though the train and subway systems are less energy dependent, it is impossible to replace all cars and buses transport with trains and subway in a short time and at the present lifestyle and urban organization. Thus, it may be better to encourage people to use smaller cars that consume less energy to run and less materials for their production.
c) Promoting new energy saving technologies, such as electric cars and bikes, that are in general more efficient and less polluting (Mellino et al., 2016).
d) Promoting policies that decrease the number of commuters (decentralization of services, help people move closer to their job place, etc).
e) Put fees on people travelling to Beijing by car, alone. Promote car-sharing. In some EU cities (e.g., Milan, Italy) people entering by car pay an entrance ticket.
f) Promote efficiency in road and vehicle industrial production. Favor more durable infrastructures (even if they may cost more) and vehicles.

Emergy merges the monetary point of view (e.g. the large costs of labor) and the energy point of view (e.g. the need for fuels and electricity), but also accounts for the environmental support to material resource generation. In fact, the UEV of minerals, fuels organic matter, also include the time needed for their replacement by natural processes. What takes more time generally has a higher UEV and is less renewable.

*Conclusions*

Previous studies about the transport sector in China only mainly focus on the regional greenhouse emissions or single transportation type (passenger or freight), which is difficult to display in a comprehensive picture. Thus, we implemented the monetary, energy and emergy evaluations of the terrestrial passenger and freight transport in China in the year 2012 in order to achieve a deeper understanding of the Chinese transport sector at the national level.
Monetary and energy evaluations display a specific aspect of the transport sector, while emergy accounting involve the social and environmental perspective compact. The evaluation results and ranking of the modalities are different for different methods. The monetary and energy results are more similar, which means the policy try to lower the economical cost also could improve the energy efficiency. The emergy results prove that the transport sector operation need more than energy, vehicles and

infrastructure. Labor and service are also necessary components for transport. Specifically, the labor intensive feature of public transportation will help to create more jobs, while limitation of private car could save more time for the driver to more productive activities.

## Chapter 6.b Electric bike implementation. A Life Cycle Assessment of lithium battery and hydrogen-FC powered electric bicycles

*Introduction*

The negative effects of increasing air pollution, climate change, depletion of fossil resources are pushing modern society to the development of alternative energy sources. Modern cities are the most interested areas where emissions deriving from the road traffic generate huge environmental problems and related negative effect on human health. On the larger scale, outside of city boundaries, traffic emissions contribute to the global worsening of environmental integrity. In fact, the transport sector is one of the major sources of greenhouse gases emissions, in addition to other environmental impacts also related to the combustion of fossil fuels. The transport sector is responsible for 30% of all fossil fuel emissions in the EU [1]. In the last years more rigorous standards for vehicle fuel consumption and emissions have been introduced. Therefore, many vehicle companies focused their research on the development of modified conventional vehicles in hybrid versions [2]. Hybrid vehicles still use fossil fuel sources, such as gasoline, and achieve an energy use reduction (and a parallel decrease of $CO_2$ emissions) due to higher engine efficiency, partially addressing the problem of pollution. However, the 2008 Italian National Research Council (NRC) report on alternative transportation technologies compared hybrid vehicles with gasoline, biofuels and hydrogen-powered fuel cell electric vehicles [3] and achieved surprising results. The report revealed that biofuels or hybrid cars would reduce greenhouse gas (GHG) emissions and oil consumption compared to business as usual, but both emissions and oil use would level off or begin rising again due to a rebound effect related to an increasing in the amount of kilometers traveled, thanks to the higher efficiency of the vehicles (as also confirmed by Thomas [4]). On the other hand, the hydrogen-powered fuel cell electric vehicles, acting alone, would set GHG emissions and oil consumption on a steady descending path.

Nevertheless, electric vehicles are believed to represent an innovative environmentally–friendly means of transportation capable of reducing the urban atmospheric pollution furthering low-carbon transportation development [5,6]. All in all, although natural gas use is likely to reduce oil consumption and promote non-negligible reductions in greenhouse gas emissions and biomass fuels such as biodiesel, bio-ethanol or bio-butanol from cellulosic feedstocks are promising, it appears increasingly clear that hydrogen and electricity will eventually drive the development of transportation technologies towards zero-carbon fuels [4].

In the context of low-carbon transportation, hydrogen fuel cells have shown notable potentialities thanks to their high-efficiency electrochemical conversion [7] as compared to less efficient, Carnot cycle combustion of conventional engines. Hydrogen fuel-cells represent a potential replacement for the internal combustion engines used in passenger vehicles also due to their comparable fueling times and ranges per fueling [8,9].

This work aims at assessing to what extent electric engines are a real cleaner solution in the transport sector. The assessment is accomplished by comparing two kinds of electric vehicle, a lithium battery powered electric bicycle (E-bike) and a hydrogen-fuel cell operated one (H-bike) by means of Life Cycle Assessment (LCA) method. A second comparison is drawn with a bike powered by an internal combustion engine. Only few studies that use LCA to compare the environmental performances of electricity powered vehicles are available in the literature, especially regarding the PEM fuel cell technology. This also applies to the comparison of typologies of electric bicycles, on the basis of their life cycle performance and related LCA indicators [10,11,12]. Most of the existing studies only address the energy benefits and costs, while other kinds of impact are disregarded. This is especially important if we think of the potential toxicity for industrial manufacturing of battery and fuel cell components as well as if we also consider the electrochemical production of hydrogen fuel. This work aims to contribute to the reduction of this knowledge gap. It is important to evaluate the environmental impacts of systems and not only the energy performance efficiency. Furthermore, to the best of our knowledge, this study is the first LCA of an electric bike fueled by hydrogen using a fuel cell. It represents, in our opinion, an important scientific and technological novelty considering that according to Jamerson and Benjamin [13] 200 million electric bicycles are used today, destined to grow to 2 billion by 2050. The PEMFC technology has shown significant potentialities for generating electricity and hydrogen produced by means of renewable energy is considered a "low emission" energy carrier. The evaluation of the environmental impacts of a H-bike represents an important contribution to understand the problems related to the use of this new technology.
The hydrogen bicycle analysed in this study uses a proton exchange membrane fuel cell (PEMFC) to convert hydrogen into electricity. Proton exchange membrane fuel cells (PEMFC) are considered to be the most suitable for use in transport applications since of their relatively low operating temperature, quick start-up time and high efficiency [9], high power density and low emissions [14,15], as proved in several experimental tests and numerical models. In literature there are different studies dealing with performance, efficiency and environmental impact assessments of PEM fuel cell powered vehicles. Cardinali et al. [16] described the construction of and the experimental test for an electric bicycle supplied by a PEM stack generator. Hussain et al. [8] provided a preliminary LCA of PEM fuel cell powered automobile focusing on energy consumption and greenhouse gases (GHGs) emissions. The evaluation included both the operation of the vehicle on the road and the production and distribution of the vehicle and the fuel (hydrogen) during the vehicle's entire lifetime. The comparison with a conventional internal combustion engine (ICE) automobile shows that the overall life cycle energy consumption of PEM fuel cell automobile is lower than that of ICE automobile and same applies to their overall life cycle GHGs emissions. Bartolozzi et al. [17] investigated the use of renewables in the realization of hydrogen production chains and the use of hydrogen as fuel in Tuscany Region (Italy). Life cycle assessment was used for evaluating the environmental sustainability of such production chains, applied to different hydrogen vehicles for urban

commercial delivery. A comparison with electric vehicles and internal combustion vehicles is also performed by the same authors: results showed that the use of renewable energy source, either for hydrogen or electricity production, has better performance on most of the considered impact categories than the use of Italian national electricity mix. Kheirandish et al. [7] investigated a PEM fuel cell powered system of an electric bicycle describing its overall efficiency. Their results suggested a maximum fuel cell efficiency of 63% and an overall system efficiency of 35.4%. The latter value is expressed with regards to the Lower Heating Value (LHV) of hydrogen. Garrain and Lechon [18] presented a LCA of the manufacturing process of a PEM fuel cell installed in a cargobike (a three-wheel assisted-pedaling vehicle). Results shown that metal components of PEMFC are the main contributors to the global warming and fossil energy use impact categories.
The added value of the present work relies on its all-encompassing overview of the entire production chain, including processes related to the energy carrier(s) and the vehicle production process at industrial level. The study also explores to what extent the energy mix of a country affects the final results in terms of the different impact indicators: as clearly understandable, it is not irrelevant if the primary energy use of a country is mainly composed with natural gas (as with Italy) instead of, say, coal (as with China), nuclear (as with France) or hydro (as with Finland), thus heavily determining the impacts of the intermediate and final products. The step-by-step and parallel-comparison oriented structure of the analysis is expected to provide very telling results concerning the environmental costs and benefits of the bicycle construction, use and their relation with the economic system in which the process is embedded. The hot spots of the production processes as well as of the energy carrier generation and use are carefully addressed and provide essential information for the improvement in the electric vehicle technology, identifying the process steps characterized by drops of efficiency and effectiveness over the whole life cycle of the investigated vehicles.

*System Boundary and Description*

In this section the main components of the analyzed hydrogen-fuel cell electric bicycle are described together with the considered system boundary. Figure 6.1 shows a system diagram of the analysed process, including the production of the hydrogen fuel and the construction and operation of the H-bike.
All the data concerning the components of H-bike are from Kheirandish et al. [7] and Cardinali et al. [16]. The bicycle presents a fuel cell system that consists of a 250 W PEMFC, an Electronic Control Unit (ECU) which monitors all of the system's parameters, a rechargeable nickel-metal hydride (Ni-MH) battery (25 V, 9 Ah), 2 DC/DC converters (2x150 W), an electric engine (150 W) and a metal-hydride hydrogen storage tank (Ø54 x L350 mm).
The PEMFC consists of 3 three main parts: a cathode, an anode that and a Nafion membrane. The PEMFC transforms the chemical energy liberated during the electrochemical reaction of hydrogen and oxygen to electrical energy. At the anode

hydrogen fuel is processed and the electrons are separated from protons on the surface of a platinum-based catalyst. The protons pass across the membrane to the cathode side of the cell while the electrons travel in an external circuit, producing the electrical output of the cell. On the cathode side, the protons and electrons are combined with oxygen to produce water that is the only waste product.
In order to include the production of the hydrogen fuel within the system boundary, it is supposed that the hydrogen was produced by a fuel station via photovoltaic (PV) driven electrolysis. The data relative to the hydrogen production are from NEEDS [20] considering that the necessary electricity is produced directly by photovoltaic panels installed on the fuel station. Furthermore, to compare the environmental impacts related to H-bike with a conventional electric bike, the data for the E-bike as well as the lithium battery (36 V, 10 Ah) production process are from the database Ecoinvent v. 3.1. The electricity to recharge the E-bike battery is supposed to be taken directly from the net using the typical Italian electric mix (also from Ecoinvent v. 3.1).

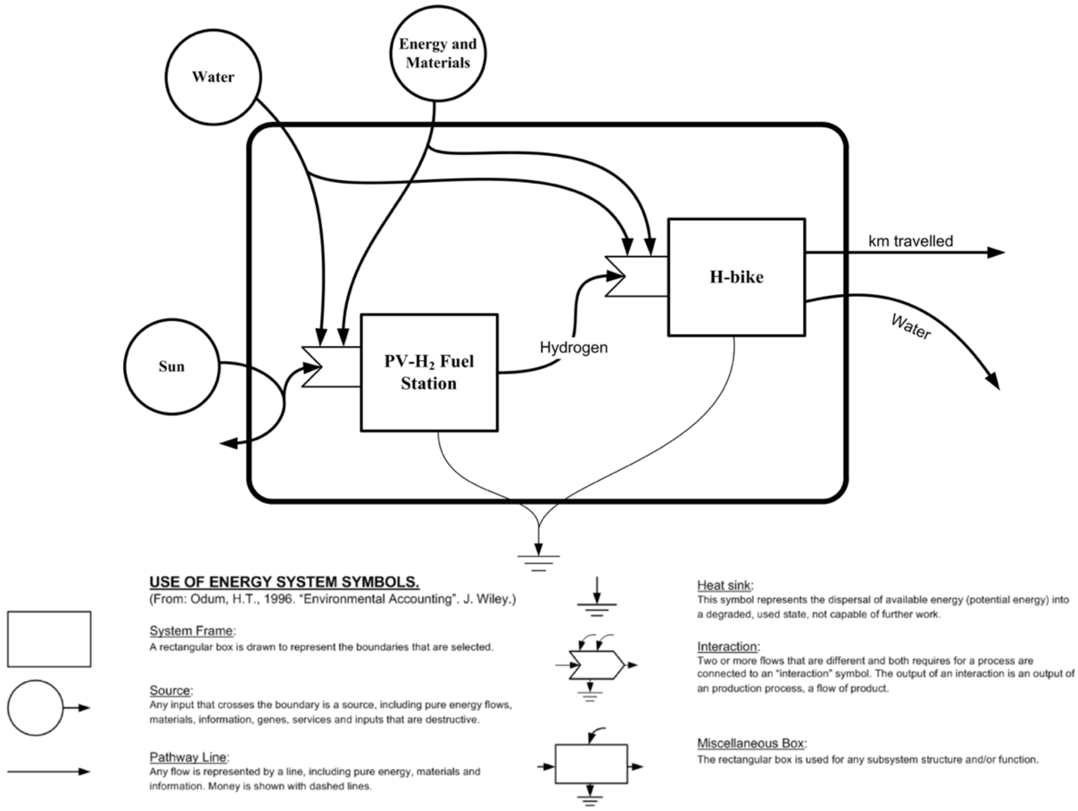


**Figure 6.1** System boundary of the analyzed system. (Systems symbols from Odum [15]).

*Life Cycle Assessment: "Well to Wheel" and "Cradle to Grave" approaches*

In this study the environmental assessment is performed according to the Life Cycle Assessment methodology as defined by ISO and ILCD standards (International Standard Organization, ISO 14040/2006 [21], ISO 14044/2006 [22], ILCD [23,24]). Life Cycle Assessment (LCA) is an analytical tool to assist environmentally relevant decision making concerning product systems. The scope of LCA encompasses development, production, use, disposal and recycling of products for specific applications. The ISO 14040/2006 [21] defines LCA as follows: “LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its entire life cycle”.

In LCA, the entire life cycle of the product of interest is described. This description includes the extraction of resources, the production of materials and intermediates from the resources, the assembly of the product from the materials, the use of the product, and the end of life. An LCA requires several steps. Most of them are done sequentially, but there are also iterative parts where the previous steps have to be reconsidered. These steps are:

- Goal and scope definition phase, where the final goal of the LCA is stated, the significant assumptions and choices in the assessment are identified, the system boundary is defined and the functional unit is set. The functional unit is the amount of the output (product or service delivered) to which all materials, emissions, cost, energy consumption, and recovery levels are referred.
- Life Cycle Inventory (LCI) phase, where input and output flows of matter and energy are listed and quantified. For an LCA study, two types of data are necessary: specific inventory data about the foreground system, and average or generic data about the background system.
- Life Cycle Impact Assessment (LCIA) phase, where the large number of resources and emissions that make up the LCI is translated into a handful of environmental impact categories. Each flow from the LCI is grouped into one or more categories. Within each category, the flows are aggregated using equivalence factors called characterization factors. These factors are based on the physical and chemical properties of the impact-causing substances, as well as on the fate of the flows once they leave the product system towards the environment. This phase also includes normalization and weighting steps, where the use of subjective values is involved to compare the different categories by each others (normalization) and to obtain single synthetic indicators (weighting). These steps are not mandatory and usually not applied when the study is intended to support a comparative assertion to be disclosed to the public [25].
- Interpretation phase, where the results of the other phases are considered collectively and analyzed in terms of the accuracy achieved and the completeness and precision of the data and the assumptions that were used. Moreover, robust conclusions and recommendations relating to the goal and scope of the study are developed in this last phase.

The impact assessment method used in this study is ReCiPe Midpoint H (http://www.lcia-recipe.net). This method allowed to assess the environmental impacts in different impact categories. The chosen categories are: Global Warming Potential (GWP, in kg $CO_2$ eq), Human Toxicity Potential (HTP, in kg 1,4-DB eq), Fossil Depletion Potential (FDP, in kg oil eq), Metal Depletion Potential (MDP, in kg Fe eq), Photochemical Oxidant Formation Potential (POFP, in kg NMVOC) and Particulate Matter Formation Potential (PMFP, in kg PM10 eq).

The ReCiPe method also provides characterization factors to quantify the contribution to impact categories and normalization factors to allow a comparison across categories [26]. Moreover, the Ecoinvent 3.1 version database (www.ecoinvent.org) is used for relevant background data related to the main inputs of the examined processes. For the estimation of the potential environmental impact of the processes considered, we used the OpenLCA software (version 1.4.2 http://www.openlca.org) integrated with the Ecoinvent 3.1 database. The calculation theory behind the software is based on matrix algebra: the inventory is converted into elementary flows[22] also considering the background processes that partially contributes to the formation of each direct input. The elementary flows are multiplied by the relative characterization factors associated with a given impact category and then the different contributions are summed up to generate the total value for each category.

As mentioned previously, the considered model splits the analysis in 2 main steps, the environmental impact assessment of the production of the vehicles and their components using a "cradle to grave" approach (CTG) and the environmental impact assessment of the energy carriers used for the operation of vehicles using a "well to wheel" approach (WTW). In the CTG approach the environmental impacts are calculated for all the stages of the life of a product, from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste [23]. The functional unit chosen for this step is 1 unit of the final product (1 bicycle) and all materials, emissions, and energy consumption are referred to this amount.

A WTW study evaluates the amount of materials and energy delivered to the vehicle wheels related with the amount of energy captured form the source, taking into account the steps of energy carriers production (electricity and hydrogen in our case) [27]. The functional unit of 100 km travelled is chosen. Transportation studies in general use a functional unit in terms of p-km, i.e. passenger per km travelled. In this case, bikes only can have one passenger riding and therefore referring only to distance is appropriate. Moreover, the impacts of the bicycles and their components (from the previous step) are allocated to the functional unit according to the lifetime of the critical elements, the lithium battery for the E-bike and the PEMFC the H-bike (24,000 km and 120,000 km respectively). In Figure 6.2 the scheme used to assess the impacts related to the vehicle usage phase is summarized.

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[22] Elementary flows: material or energy flows entering the system under study that have been drawn from the environment without previous human transformation; or, material or energy flows leaving the system, released into the environment without subsequent human transformation [21,22].

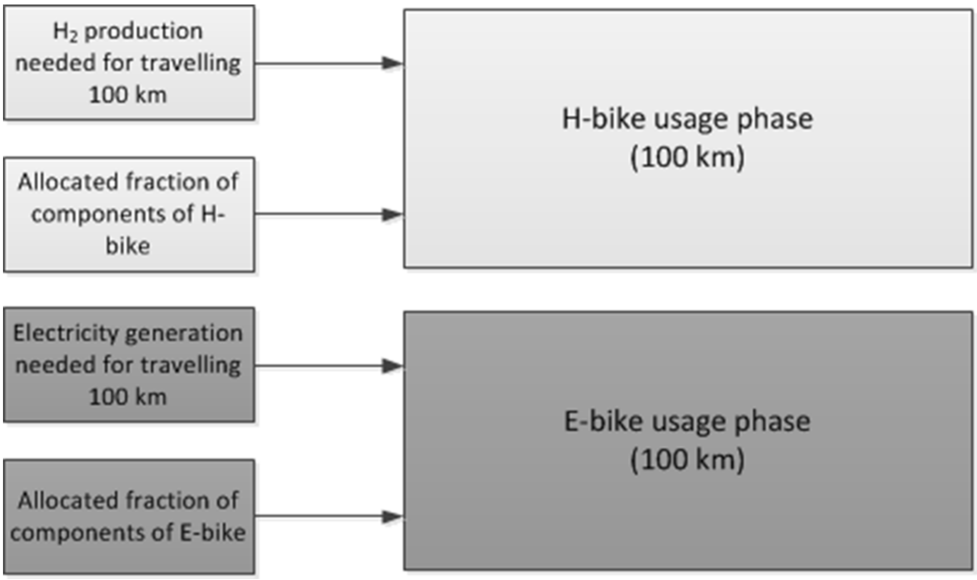


**Figure 6.2** LCA scheme used to assess for the impacts related to the vehicle usage phase.

The two used approaches have different starting points, that are the same for the two bicycles. The CTG approach starts from the extraction of the primary materials needed for the construction of the two bikes. The WTW approach starts considering the primary materials for the construction of the bikes allocated to the functional unit of 100 km traveled (i.e. only the fraction of the bicycles contributing to the functional unit is considered, taking into account the life time of the vehicles) as well as the primary materials needed for the generation of the energy carriers (electricity and hydrogen) for 100 km travelling.

*Main Assumptions*

For the E-bike an assumption is made that the 36 V, 10 Ah Li-battery has 800 cycles of charge. Considering that with 1 charge it is possible to travel for about 30 km, the calculated lifetime is of 24,000 km. The efficiency of charge and discharge of Li-battery is considered constant for all the life time of the battery. This assumption is "conservative" in fact considering the reduction of the efficiency during the life of the battery would generate a higher impact on the environment. For the H-bike we assumed that the total distance travelled during the entire lifecycle of the PEM fuel cell are about 120,000 km, as suggested by the U.S. Department of Energy (http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/accomplishments.pdf). Furthermore, the E-bike requests 0.36 kWh of electricity for 1 charge (36 V x 10 Ah x 0.001 kW $W^{-1}$) and consequently 1.2 kWh per 100 km travelled. The H-bike needs about 75 g of hydrogen to travel for 100 km [16].

*Results and Discussion*

*LCA of H-bike and E-bike production chains. The "cradle to grave" approach.*

Results from the LCA of the production processes of the 2 different bicycles and their components are presented in Table 1. The H-bike production process results more impacting in all the considered categories (Table 6.11, Figure 6.2) due to the higher complexity and the special materials used in the production chain, particularly related to the electronic control unit (ECU) and the presence of the PEM fuel cell.
The chart in Figure 6.3 shows the relative proportion between the category indicators related to the 2 analyzed bicycles. For each indicator, the highest value of the impact is set to 100%, a usual procedure in displaying LCA results, and the results of the second option are displayed in relation to the former.

*Table 6.11 Impact assessment results of the H-bike and E-bike production chains.*

| Impact category | Reference unit | E-bike | H-bike |
|---|---|---|---|
| Climate Change (GWP) | kg $CO_2$ eq | 165.13 | 276.35 |
| Fossil depletion (FDP) | kg oil eq | 41.22 | 66.26 |
| Human toxicity (HTP) | kg 1,4-DB eq | 229.90 | 580.86 |
| Metal depletion (MDP) | kg Fe eq | 118.48 | 175.90 |
| Particulate matter formation (PMFP) | kg PM10 eq | 0.52 | 1.04 |
| Photochemical oxidant formation (POFP) | kg NMVOC | 0.67 | 1.21 |

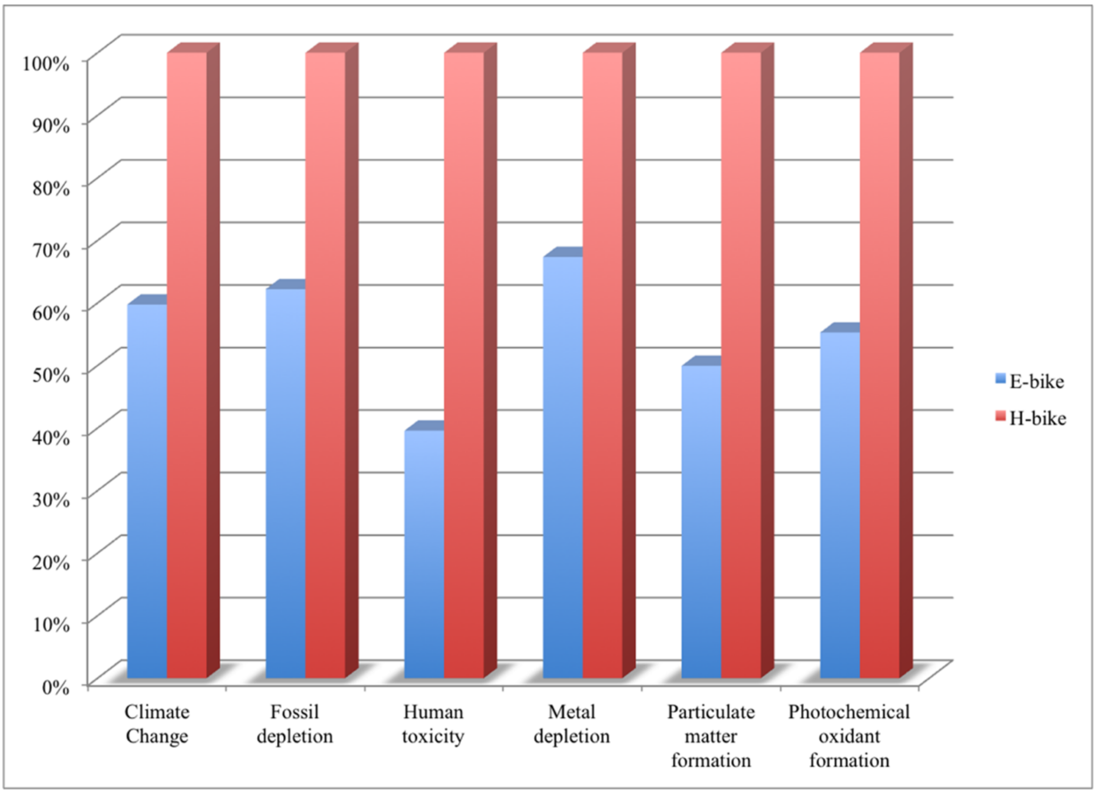

**Figure 6.3** Relative indicator results of the H-bike and E-bike production chains (For each indicator, the maximum result is set to 100% and the results of the second option are displayed in relation to the former).

In order to compare the impact categories with each other a normalization procedure is applied by means of the Recipe Midpoint H normalization factors Europe 2000 [26]. Normalization is an optional step in LCA that allows comparison across categories. As shown in Figure 6.4 both processes mainly impact on human toxicity and the H-bike generates an impact about 2.5 times higher than the E-bike (respectively 580.86 and 229.90 kg 1,4-Dichlorobenzene equivalent – Table 6.11). Moreover, the normalized results also show a non-negligible effect on metal depletion category. Minor impacts are shown by climate change, fossil depletion, particulate matter formation and photochemical oxidant formation categories.

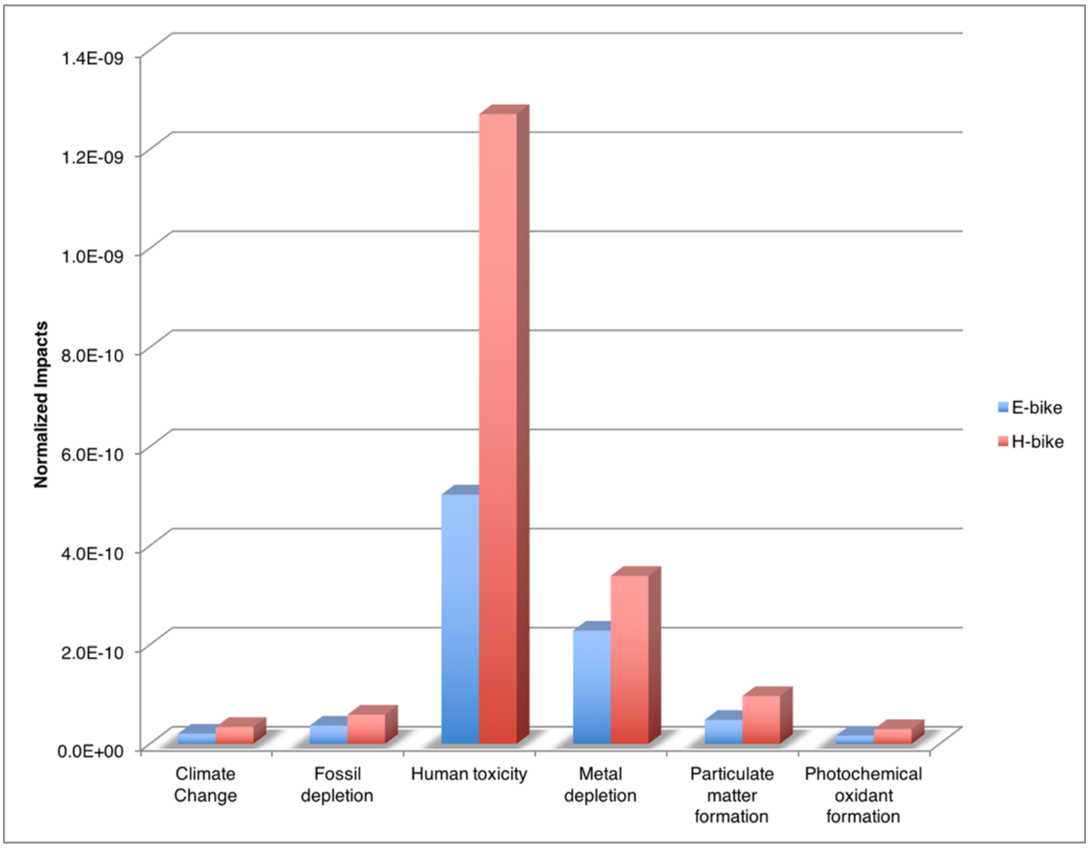


**Figure 6.4** Normalized impacts calculated for the comparison among H-bike and E-bike production chains. Normalization factor from Sleeswijk et al. [22].

By analyzing the contribution to human toxicity category of the different processes converging to the construction of the H-bike (Table 6.12, Figure 6.5) the largest impacts are represented by the electronic control unit (ECU) and DC/DC convertor (about 77% of the total impact). In fact, the production chains of the metals necessary to the construction of circuits release toxic compounds as manganese, arsenic ion,

selenium and lead, causing the elevated impact on the human toxicity category.
The difference between the 2 kinds of bikes that provides an effect on human toxicity category is mainly related to the 2 different ECUs installed. The ECU monitors all the system's parameters such as the stack temperature, hydrogen pressure, stack voltage, stack current, battery voltage, and ambient condition and operates the fuel cell during the start, normal operation, and shutdown procedures [7]. The electronic control unit of the H-bike is more complex than the one installed on the E-bike and its production process releases larger emissions of toxic compounds as manganese and arsenic ion. Furthermore, the presence of the fuel cell stack in the H-bike is an additional reason for higher impacts. The PEMFC system contributes to human toxicity about 30 kg 1,4 DB equivalent (i.e., 5% of the total).

*Table 6.12 Input contribution to the human toxicity impact category of the H-bike production chain.*

| **Process** | **Amount kg 1,4 DB eq.** | **% on the total impact** |
|---|---|---|
| Electronic Control Unit | 339.75 | 58.49% |
| DC/DC convertor | 106.94 | 18.41% |
| Bicycle frame and main components | 72.73 | 12.52% |
| Fuel cell stack | 29.99 | 5.16% |
| NiMH battery | 23.11 | 3.98% |
| Electric motor | 8.03 | 1.38% |
| Hydrogen tank | 0.30 | 0.05% |
| **Total** | **580.85** | |

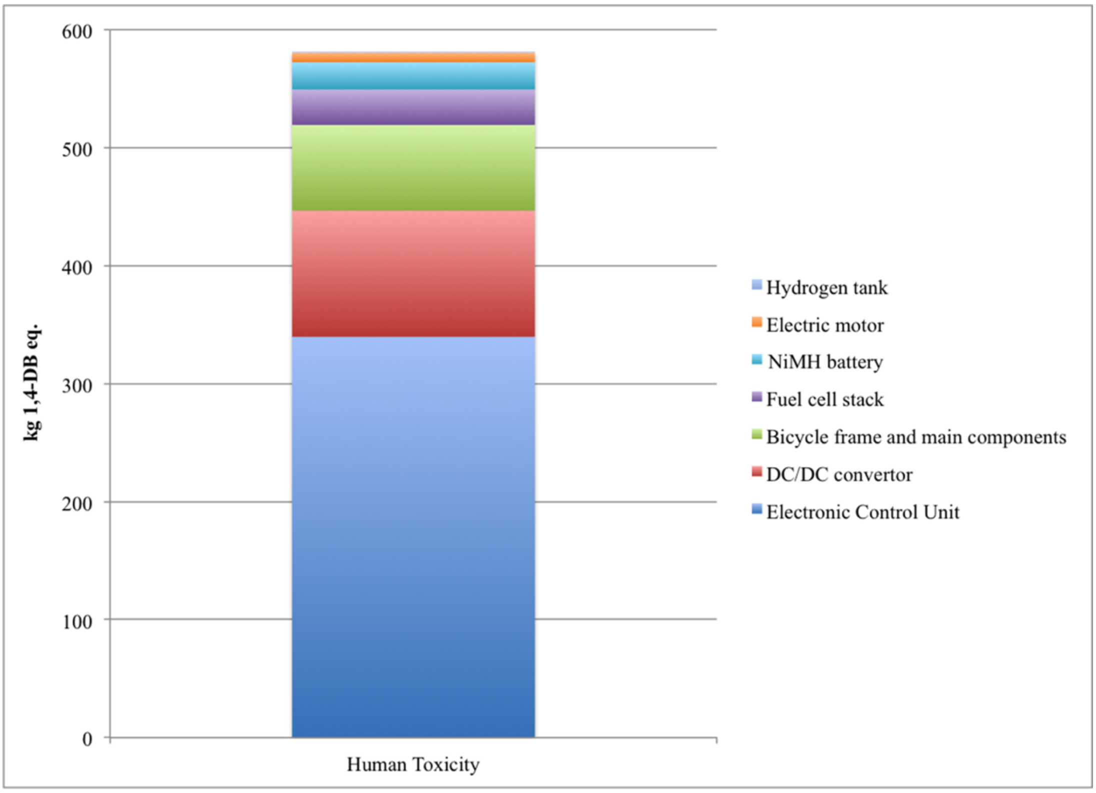


**Figure 6.5** Inputs contribution to human toxicity impact category of H-bike production chain.

*Environmental impacts of H-bike and E-bike operation. The "well to wheel" approach*

The main results of the comparison between the 2 bicycles during the use phase are shown in Table 6.13, where the performance of the H-bike ranks better than the E-bike in all the considered categories. The H-bike presents an impact on global warming and on fossil fuels depletion about 80% less than E-bike thanks to the utilization of a cleaner energy source (solar radiation) for the production of the energy carrier (hydrogen). Of course, if a renewable source is also used for the E-bike, the picture might be different. To this purpose, a scenario in which a renewable electric mix for charging the E-bike battery is also assessed later in this paper.

*Table 6.12 Impact assessment results of H-bike and E-bike usage phase (100 km travelled).*

| Impact category | Reference unit | E-bike | H-bike |
|---|---|---|---|
| Climate Change (GWP) | kg $CO_2$ eq | 1.42 | 0.31 |
| Fossil depletion (FDP) | kg oil eq | 0.40 | 0.07 |
| Human toxicity (HTP) | kg 1,4-DB eq | 1.07 | 0.55 |
| Metal depletion (MDP) | kg Fe eq | 0.51 | 0.31 |
| Particulate matter formation (PMFP) | kg PM10 eq | 3.07E-03 | 1.35E-03 |
| Photochemical oxidant formation (POFP) | kg NMVOC | 4.50E-03 | 1.39E-03 |

The normalized indicators (Figure 6.6) confirm that the more impacting category is the human toxicity also in the usage phase of the 2 bicycles; nonetheless, the situation is now the opposite than before. The H-bike impacts less since the lifetime of the PEM fuel cell system is higher than the Li-battery and also because the PEMFC system presents a higher efficiency in the conversion of the energy feedstock in electric energy.

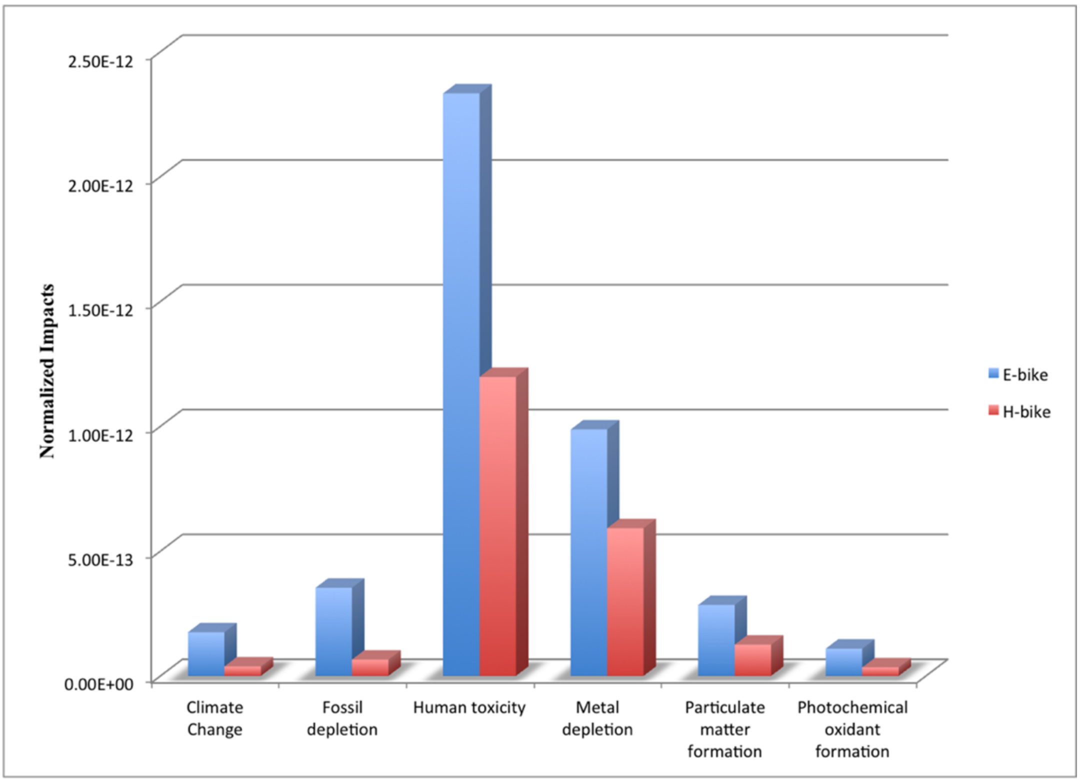


**Figure 6.6** Normalized impacts calculated for the comparison among usage phase of H-bike and E-bike (100 km travelled). Normalization factor from Sleeswijk et al. [22].

*A comparison with a renewable electric mix for sensitivity purpose.*

In order to assess the performance dependence of the electric bike upon a given electric mix, a scenario is built in which a green and renewable electric mix is supposed to be used for charging the battery instead of the national grid mix. The assumption is made based on data from Enel Green Power, that is a society of the Italian ENEL Group (the largest electricity producer in Italy) that develops and manages energy generation from renewable sources at a global level, with a presence in Europe, Americas, Asia and Africa (http://www.enelgreenpower.com/en-GB/). The "Enel Green Power" mix adopted in this scenario is calculated based on the different generation sources installed in Italy. It includes 49.9% of hydroelectric, 23.8% of geothermal, 23.7% of wind and 2.6% of solar. Furthermore, the results are compared with a motor scooter used as a benchmark to compare the electric technology with the internal combustion ones. The data for the motor scooter are from the database Ecoinvent 3.1. The Figure

6.7 shows that the use of a renewable mix for the E-bike battery re-charge produced an improvement in all the considered categories, mainly in global warming and fossil depletion in comparison with the use of the Italian electric mix. The H-bike still remains the vehicle with the lowest impact in all the categories, but it is clear now that this is due to the higher PEMFC efficiency and longer lifetime. According to Lee et al. [28,29] the production of hydrogen via renewable sources shows large environmental advantage and this is a crucial point to confirm the better performance of PEMFC vehicles compared to others. The internal combustion engine technology results the worst alternative especially in all the categories related to the direct emissions occurring during the operational phase. The results of the categories as human toxicity and metal depletion suggest that further technical improvements in material choices and in the production processes of components are needed for electric technology.

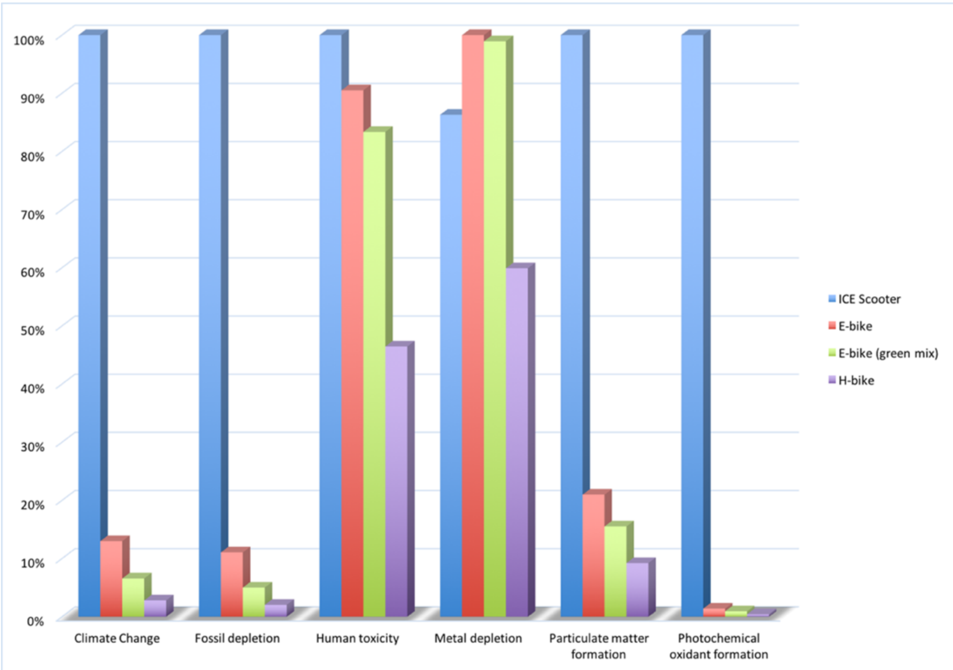


**Figure 6.7** Relative indicator results calculated for the comparison among usage phase of ICE-Scooter, H-bike, E-bike and E-bike using a renewable electric mix for battery charging (100 km travelled). For each indicator, the maximum result is set to 100% and the results of the other options are displayed in relation to the former.

In conclusion, this study is highly illuminating concerning the environmental costs and benefits of different technologies for the urban transport sector, as far as energy, materials and emissions are concerned. The application of a fuel cell to an electric bicycle may represent an important improvement aimed at energy savings, air pollution and global warming reduction. Results of this study highlight that the electric bike is, anyway, less impacting than an internal combustion vehicle, and that the energy (and electricity) mix of a country has a huge influence on environmental impacts and therefore is an important option for improvement (i.e., recharging

batteries and generating hydrogen by using a renewable energy mix largely decreases the impacts). Finally, results also show something that remains hidden when only an energy cost or energy efficiency study is performed, namely that human toxicity impacts related to the electronic components of both bikes are non-negligible and call for efforts for replacement or recycling of these components. During the United Nations Climate Change Conference (Cop21) held in Paris in 2015, the theme of sustainable transport was also discussed and it clearly appeared that a transition is needed and the main transport companies are investing a large amount of financial and technological resources in research to meet sustainability goals.
In cities like Beijing where air pollution represents a urgent problem, the transition to electric transport has already been adopted as a solution. Moreover, electric bikes (and electric engines in general) are more and more spreading in modern cities and towns. A transition to cleaner technology like fuel cells is a further step towards sustainable transport. Still, as already suggested by Bartolozzi et al. [17], Lee et al. [28,29], Cetinkaya et al. [30], among others, this study confirmed that the source for generating the energy carrier (i.e., electricity, hydrogen) needs to be a renewable one.

***Conclusion***

A LCA approach is used in this work to evaluate the environmental impacts related to the production of a PEM fuel cell electric bicycle and the impact related to its operation phase. In both case the results are compared with the ones obtained from a like analysis of a Li-battery electric bicycle. In summary, the following conclusions can be drawn:

a) The results of the LCA from “cradle to grave” evaluation of the 2 systems displayed that the construction of the H-bike results more impacting than the E-bike in all the considered categories due to the presence of a more complex electronic control unit (ECU). This is where potential technological improvements should be pursued.
b) The human toxicity category is the more impacted one. The production processes of the ECU and DC/DC convertor release toxic compounds as manganese, arsenic ion, selenium and lead, causing a heavy environmental impact. Replacement of at least some of these materials (when possible) or their recycle would likely help decrease the impacts of production.
c) The environmental performance of the H-bike is better than the one of E-bike in all the considered categories when the boundary is shifted to the operational phases of the vehicles and calculation includes the quality of energy carriers used.
d) The energy mix used for manufacturing steps as well as the electricity mix used for battery recharging and hydrogen production may have huge environmental impacts depending on the country where the process occurs.

In light of these results, future efforts are needed to achieve a technological improvement of the electronic components of the PEMFC bicycle in order to reduce the amount of metals used and the emission of toxic compounds related to their production processes. Nevertheless, the PEM fuel cell technology represents a valuable option towards a cleaner solution for the transport sector from an environmental point of view, while its economic feasibility is still to be proven. Therefore, a Life Cycle Costing Assessment is recommended to understand the economic costs and benefits of fuel cell systems applied to the transport sector within the present and future market dynamics.

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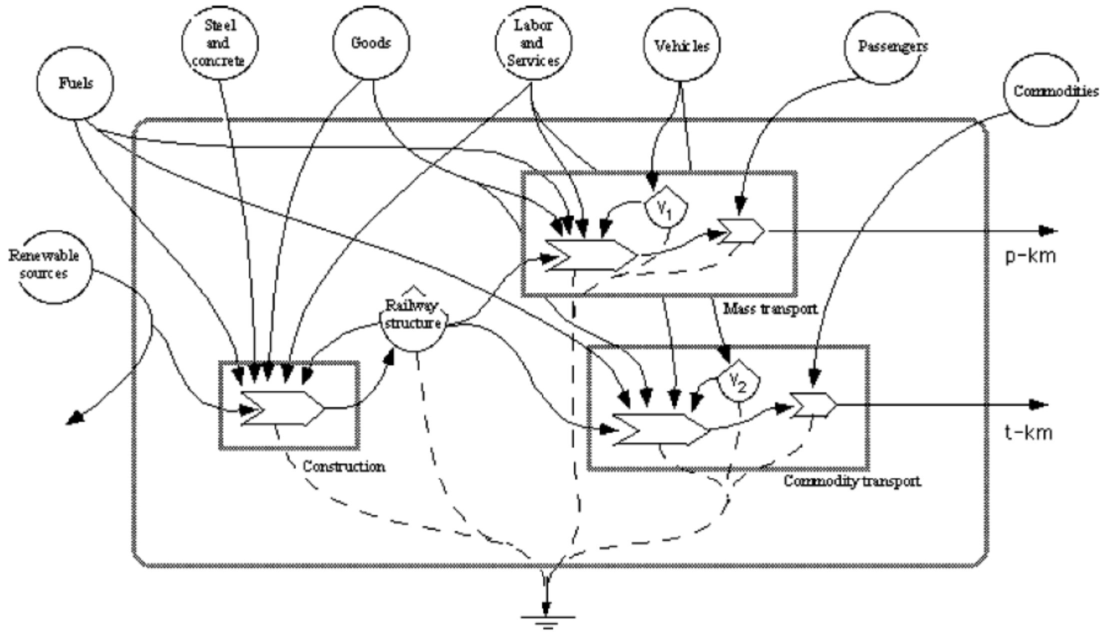
# Chapter 6.c Terrestrial transport modalities in Italy.

# A benchmark.

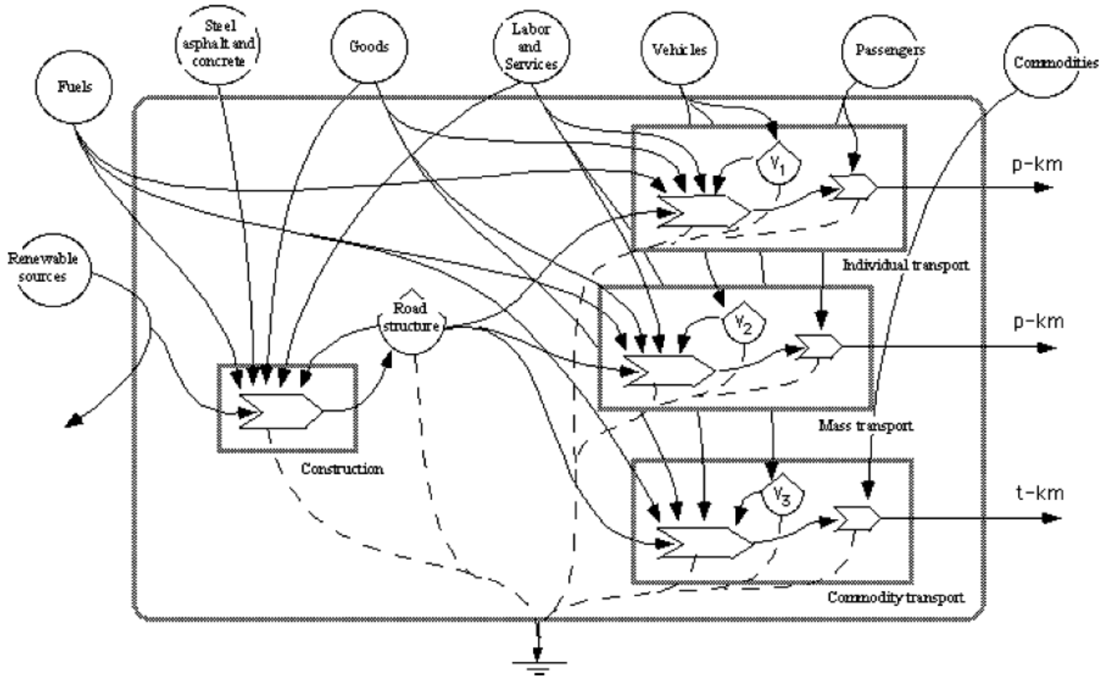
The present study deals with the energy and environmental performances of local and national transport systems in Italy, with focus on both passenger and commodity transportation, by means of road and rail modalities. Case studies of urban systems of Siena and Brescia as well as the highway, intercity rail and high speed rail systems connecting Milano and Napoli are investigated, to serve as a benchmark for comparison with other performances of systems elsewhere (see for example this deliverable, Chapters 6.a and 6.b).
Figures 6.8a,b show the system diagrams of rail and road modalities, showing renewable and non-renewable input flows supporting the systems as well as the main systems components, including infrastructure construction.

The cities of Brescia (Northern Italy) and Siena (Central Italy) were investigated as urban transport case studies on the local scale. Brescia is located on a very important traffic, rail and freight axis of Italy, the Turin-Venice axis, and its economy is characterized by widespread industrialization. In contrast, Siena is situated in a less accessible zone and its economy is based mainly on agriculture and services. Although different from a geographical, morphological and economical point of view, these two provincial districts are similar from the point of view of some macroeconomic variables, like per capita income, and are also comparable with respect to the size of their two main towns.

The economic structure of Brescia is mainly based on a well-developed industrial sector (iron and steel manufacturing, machinery, textile and local clusters specialized in producing components for big industries). This intense economic activity generates critical levels of chemical and dust emissions, production of waste, and road traffic. In the urban area, the attention and alarm thresholds of airborne chemical concentrations are very often exceeded, especially in winter, requiring the city administration to forbid car use for several days. The transport sector accounts for about 28% of the total Brescia energy consumption, while it is 33% of total national consumption). Road and railway subsystems are the main means of transportation in the area. The province of Siena has a surface of 3,820 km$^2$, dominated by a hilly landscape (92%). The economic structure of the district is centered on a well-developed and high added value agricultural activity, as well as on a service sector of banking, university, tourism and health care activities. A low population density and little industrial activity, make the level of pollution (traffic, noise, production of waste, release of chemicals, etc.) low and quite acceptable (i.e., people perceive it as acceptable). The transport sector represents about 39% of total energy consumption and related airborne emissions for the province. The railway system is based on an old fleet of diesel-powered trains, mainly used for transporting daily commuters to their villages outside of Siena.




(a)




(b)

Figure 6.8. (a) Systems diagram of railway modality. (b) Systems diagram of road modality. V1, V2, and V3 indicate vehicles and other assets provided to the system and allocated over their life-time.

Due to incentives offered by the Italian government to favor the decommissioning of old cars, in both urban areas the automobiles provide improved control of air quality. Old cars replaced by brand new models in the last five years represent 35% of the total circulating fleet in Siena and 33% in Brescia. However, the transport system is perceived by the population as the main environmental problem in both areas, although Brescia is also heavily affected by industry-related pollution.
Table 6.14 shows energy intensities at both local and global scales. Energy intensity at global scale also includes the energy used indirectly over the entire supply chain of vehicles and infrastructure, properly allocated over its lifetime. Ratios of global-to-local energy intensities show an approximate increase of energy use by 20%. This means that the most important energy costs are those related to direct energy use. The emergy analysis method, instead, also account for the environmental cost of materials (i.e. their production by nature) and therefore the relative weight of direct energy becomes smaller, although still dominant.

The global-to-local energy ratio can be calculated from Tables 6.14 and 6.21 and provides values in the range 1.1-1.4 to 1 for liquid fuel vehicles and up to 2-3 to 1 for electric modalities (railway), indicating that the larger fraction of energy is used locally by road modalities and indirectly in power plants by railway systems. This does not necessarily mean that railway systems consume less energy (depending on occupancy rate, efficiency of engine, etc), but provides an indicator of where efforts should be applied for improvement of global efficiency.

Table 6.14. Performance of the transportation systems in Siena and Brescia, Italy.

| | unit | Mass Flow Accounting Local scale (*) (kg/unit) | Energy Accounting Local scale (MJ/unit) | Energy Accounting Global scale (MJ/unit) | Exergy Analysis Local scale (MJ/unit) | Emergy Analysis Global scale ($10^{11}$ sej/unit) |
|---|---|---|---|---|---|---|
| | | | | **Siena** | | |
| **Passenger transport (*)** | | | | | | |
| Road individual transport | (p-km) | 0.19 | 1.75 | 2.10 | 1.63 | 1.66 |
| Road mass transport | (p-km) | 0.07 | 0.49 | 0.62 | 0.47 | 0.60 |
| Railway (diesel) | (p-km) | 0.12 | 0.61 | 0.73 | 0.58 | 0.74 |
| **Commodity transport (*)** | | | | | | |
| Road | (t-km) | 0.50 | 1.59 | 1.66 | 1.29 | 3.11 |
| Railway (diesel) | (t-km) | 0.95 | 0.30 | 0.42 | 0.28 | 4.17 |
| | | | | **Brescia** | | |
| **Passenger transport (*)** | | | | | | |
| Road individual transport | (p-km) | 0.17 | 1.76 | 2.12 | 1.74 | 2.47 |
| Road mass transport | (p-km) | 0.06 | 0.12 | 0.21 | 0.11 | 0.37 |
| Railway (diesel) | (p-km) | 0.61 | 0.18 | 0.85 | 0.17 | 3.58 |
| Railway (electric) | (p-km) | 0.14 | 0.52 | 1.76 | 0.47 | 1.87 |
| **Commodity transport (*)** | | | | | | |
| Road | (t-km) | 0.27 | 1.68 | 2.08 | 1.61 | 1.91 |
| Railway (diesel) | (t-km) | 9.21 | 1.90 | 2.70 | 1.89 | 39.82 |
| Railway (electric) | (t-km) | 2.10 | 0.14 | 0.67 | 0.13 | 13.34 |

(*) MFA is only calculated here on the local scale, and indicates the mass of system allocated to each unit of product. However, most MFA analysts also account for the mass indirectly involved at larger scale (LCA scope)

Table 6.15 shows the main emissions of the transportation system of Siena at the local and global scales. Direct emissions are mainly related to local fuel use, while indirect refer to vehicle and infrastructure construction as well as electricity generation to run the rail system. The local diesel train connecting Siena to Florence and to Chiusi is also included.

Table 6.16 provides a breakdown of the emergy input in each transport modality in Siena and Brescia (expressed as % of total environmental support demand). From this table it is possible to understand that the relative importance of vehicles, infrastructure, direct energy use and labor&services depend on the specific case and vehicle occupancy. It appears that resources are allocated very differently in the railway modality than in the road modality: railway requires more resources for infrastructure, while the road system is more demanding for direct energy use.

Table 6.15. Main local and global scale emissions of the transportation system in Siena, Italy.

| | Unit | $CO_2$ (g/unit) | CO (g/unit) | $NO_x$ (g/unit) | PM[a] (g/unit) | VOC (g/unit) | $SO_x$ (g/unit) |
|---|---|---|---|---|---|---|---|
| Passenger transport | | | | | | | |
| Road individual transport | | | | | | | |
| Local scale | p-km | 109.46 | 3.72 | 1.21 | 0.020 | 0.85 | 0.330 |
| Global scale | p-km | 121.70 | 3.75 | 1.26 | 0.024 | 0.86 | 0.331 |
| Increase (%) | | 11.19 | 0.72 | 4.44 | 20.31 | 0.13 | 0.30 |
| Road mass transport | | | | | | | |
| Local scale | p-km | 33.75 | 0.210 | 0.610 | 0.040 | 0.07 | 0.09 |
| Global scale | p-km | 35.10 | 0.212 | 0.614 | 0.041 | 0.07 | 0.10 |
| Increase (%) | | 4.10 | 1.34 | 0.96 | 1.33 | 0.15 | 4.44 |
| Railway mass transport | | | | | | | |
| Local scale | p-km | 41.21 | 0.140 | 0.530 | 0.060 | 0.060 | 0.120 |
| Global scale | p-km | 45.60 | 0.148 | 0.546 | 0.063 | 0.062 | 0.123 |
| Increase (%) | | 9.72 | 5.73 | 3.32 | 2.68 | 0.56 | 3.28 |
| Commodity transport | | | | | | | |
| Road | | | | | | | |
| Local scale | t-km | 0.09 | 0.56 | 1.65 | 0.11 | 0.20 | 0.30 |
| Global scale | t-km | 0.107 | 0.57 | 1.69 | 0.20 | 0.201 | 0.3 |
| Increase (%) | | 14.59 | 2.36 | 2.27 | 87.66 | 0.78 | 0.09 |
| Railway | | | | | | | |
| Local scale | t-km | 0.01 | 0.03 | 0.10 | 0.01 | 0.01 | 0.06 |
| Global scale | t-km | 0.02 | 0.05 | 0.16 | 0.02 | 0.012 | 0.061 |
| Increase (%) | | 88.14 | 65.96 | 60.44 | 99.09 | 18.56 | 3.33 |

[a] Includes all kind of particulate matter.

Table 6.16. Allocation (%) of emergy input to transport typologies, disaggregated into the main input categories.

| Sub-System | Renewable (§) | Structure (*) | Infrastructure (**) | Directly Energy Use (°) | Labor and services (#) |
|---|---|---|---|---|---|
| **Road transport, Siena** | | | | | |
| Individual transport, car | 0.008% | 12.68% | 3.18% | 49.43% | 33.77% |
| Road mass transport, bus | 0.032% | 6.76% | 13.31% | 64.28% | 14.80% |
| Road goods transport, truck | 0.097% | 0.37% | 40.48% | 34.02% | 22.54% |
| **Road transport, Brescia** | | | | | |
| Individual transport, car | 0.002% | 13.28% | 0.89% | 52.15% | 33.59% |
| Road mass transport, bus | 0.014% | 29.05% | 5.92% | 25.68% | 38.73% |
| Road goods transport, truck | 0.044% | 1.72% | 17.83% | 69.94% | 8.63% |
| **Diesel railway transport, Siena** | | | | | |
| Railway mass transport | 0.01% | 6.48% | 28.31% | 26.59% | 38.61% |
| Railway goods transport | 0.02% | 0.16% | 70.12% | 1.70% | 27.99% |
| **Diesel railway transport, Brescia** | | | | | |
| Railway mass transport | 0.01% | 20.83% | 53.32% | 7.99% | 17.82% |
| Railway goods transport | 0.02% | 0.24% | 74.28% | 2.97% | 22.45% |
| **Electric railway transport, Brescia** | | | | | |
| Railway mass transport | 0.01% | 0.34% | 36.62% | 13.53% | 49.15% |
| Railway goods transport | 0.02% | 0.07% | 62.16% | 18.60% | 19.13% |

(§) Only the direct solar radiation impinging on the interested area is accounted for as Renewable Emergy. This corresponds to the solar emergy that supported the sustainable ecosystem previously existing in this area before the system of roads and railway were constructed.
(*) Only vehicles (cars, trains, trucks) are included in this item. Emergy supporting labor and services is not included.
(**) All kinds: roads, bridges, railway, etc are included. Emergy supporting labor and services is not included.
(°) Fuel and electricity.
(#) Includes direct labor as well as indirect labor quantified as services and measured by the economic value of the items supplied.

**The National System: The Milan-Naples Axis**

The Milan-Naples axis is the most important traffic line in Italy connecting the economic core of Northern Italy, the Milan area, with the biggest and more populated city of Southern Italy, Naples. Rome, Florence and Bologna are also served by this transportation infrastructure. The axis is composed by three parallel sub-systems: the A-1 Toll-Highway, the present electric railway, and the high-speed railway, HSR. Each sub-system covers a length of about 800 km.

According to Table 6.16, infrastructure construction and maintenance costs are not negligible, in spite of their allocation over a generally long time span. They affect the total cost of railway modality much more than for the highway modality. Calculating costs by means of the emergy method provides a joint assessment of materials, energy, labor and know how needed, yielding a very comprehensive picture of the sustainability of a given transportation mode. Tables 6.17 and 6.18 provide an assessment of construction and maintenance costs of the highway and high speed rail modalities, over the Milan-Naples axis. It clearly appears that the total emergy demand for HSR/TAV (high speed rail/treno alta velocita') infrastructure is about 4.6 times higher than for the highway infrastructure.

Table 6.17. Inventory and emergy analysis of the Milan-Naples Highway construction and maintenance.

| Item | Unit | Annual Amount | Solar Transformity (seJ/unit) | Solar Emergy (seJ/Year) |
|---|---|---|---|---|
| Sunlight | J/year | 9.62E+16 | 1.00E+00 | 9.62E+16 |
| Rain water (chemical potential) | J/year | 9.44E+13 | 1.82E+04 | 1.72E+18 |
| Deep heat | J/year | 6.60E+13 | 6.06E+03 | 4.00E+17 |
| **Construction of road infrastructure** | | | | |
| Gravel | kg/year | 2.46E+08 | 5.00E+11 | 1.23E+20 |
| Top soil | J/year | 8.04E+14 | 7.40E+04 | 5.95E+19 |
| Ballast | kg/year | 6.80E+08 | 5.00E+11 | 3.40E+20 |
| Asphalt | J/year | 1.72E+15 | 3.47E+05 | 5.96E+20 |
| Concrete | kg/year | 4.48E+07 | 1.03E+12 | 4.62E+19 |
| Reinforced concrete | kg/year | 4.45E+06 | 1.31E+12 | 5.85E+18 |
| Reinforced concrete traffic divider | kg/year | 2.64E+07 | 1.31E+12 | 3.47E+19 |
| Diesel | J/year | 1.21E+12 | 6.60E+04 | 7.98E+16 |
| Steel in machinery | kg/year | 8.53E+02 | 6.70E+12 | 5.71E+15 |
| Steel in tunnel reinforcement | kg/year | 1.54E+07 | 6.70E+12 | 1.03E+20 |
| Steel in guardrail | kg/year | 4.30E+06 | 6.70E+12 | 2.88E+19 |
| Steel in traffic divider | kg/year | 2.15E+06 | 6.70E+12 | 1.44E+19 |
| Labor | J/year | 4.47E+09 | 1.29E+07 | 5.76E+16 |
| Service | €/year | 2.20E+08 | 1.30E+12 | 2.86E+20 |
| **Maintenance** | | | | |
| Diesel | J/year | 5.75E+13 | 6.60E+04 | 3.80E+18 |
| Steel in machinery | kg/year | n.d. | 6.70E+12 | 0.00E+00 |
| Labor | J/year | 4.06E+10 | 1.29E+07 | 5.24E+17 |
| Service | €/year | 1.86E+06 | 1.30E+12 | 2.42E+18 |
| **Self consumption of Highway society** | | | | |
| Methane | J/year | 9.69E+12 | 5.22E+04 | 5.06E+17 |
| Diesel | J/year | 6.23E+13 | 6.60E+04 | 4.11E+18 |
| Gasoline | J/year | 4.22E+13 | 6.60E+04 | 2.79E+18 |
| LGP | J/year | 6.10E+11 | 6.60E+04 | 4.03E+16 |
| Crude oil | J/year | 1.60E+12 | 6.60E+04 | 1.06E+17 |
| Electricity | J/year | 1.34E+14 | 1.50E+05 | 2.01E+19 |
| **Total Emergy for Highway Infrastructures** | | | seJ/yr | **1.67E+21** |

Table 6.18. Inventory and emergy analysis of the Milan-Naples High Speed Train construction and maintenance.

| Item | Unit | Annual Amount | Solar Transformity | Solar Emergy |
|---|---|---|---|---|
| | | | (seJ/unit) | (seJ/year) |
| Sunlight | J/year | 5.30E+16 | 1.00E+00 | 5.30E+16 |
| Rain water (chemical potential) | J/year | 4.32E+13 | 1.82E+04 | 7.87E+17 |
| Deep heat | J/year | 2.89E+13 | 6.06E+03 | 1.75E+17 |
| **Construction of railway infrastructure** | | | | |
| Sand and gravel | kg/year | 5.27E+09 | 5.00E+11 | 2.64E+21 |
| Top soil | J /year | 4.42E+16 | 7.40E+04 | 3.27E+21 |
| Concrete | kg /year | 7.34E+08 | 1.03E+12 | 7.56E+20 |
| Reinforced concrete | kg /year | 5.53E+07 | 1.31E+12 | 7.26E+19 |
| Diesel | J/year | 8.87E+13 | 6.60E+04 | 5.85E+18 |
| Steel in machinery | kg/year | 2.65E+03 | 6.70E+12 | 1.78E+16 |
| Steel in track | kg/year | 1.85E+07 | 6.70E+12 | 1.24E+20 |
| Steel in electric poles | kg/year | 1.25E+06 | 6.70E+12 | 8.40E+18 |
| Steel in tunnel reinforcement | kg/year | 5.00E+07 | 6.70E+12 | 3.35E+20 |
| Copper in electric cables | kg/year | 3.86E+05 | 6.80E+10 | 2.62E+16 |
| Service | €/year | 3.68E+08 | 1.30E+12 | 4.78E+20 |
| Labor | J/year | 5.16E+10 | 1.29E+07 | 6.65E+17 |
| **Maintenance** | | | | |
| Electricity | J/year | 2.10E+13 | 1.50E+05 | 3.15E+18 |
| Steel in machinery | kg/year | 3.67E+04 | 6.70E+12 | 2.46E+17 |
| Service | €/year | 3.81E+06 | 1.30E+12 | 4.95E+18 |
| Labor | J/year | 8.30E+10 | 1.29E+07 | 1.07E+18 |
| **Total Emergy for TAV Infrastructures** | | | **seJ/yr** | **7.70E+21** |

Infrastructure costs, properly allocated to each modality, must be added to operation costs (Tables 6.19 and 6.20). Total costs are splitted in the Tables into costs for commodity transport and costs for passenger transport. Concerning passengers, the total emergy demand for the highway system is about 5 times higher than for the High Speed Rail, thus reversing the picture provided by construction costs. Same for commodities, where the cost of highway operations is about 15 times higher than for HSR.

However, totals in Tables Tables 6.17 to 6.20 are not complete, being an assessment of costs without appropriate comparison of the transport service provided. If total costs are calculated per unit of service, we obtain the unit results shown in Table 6.21, that allows full comparison of passenger and transport modalities per unit of transport service (p-km and t-km). Results from Table 6.21 can be compared with results in Table 6.14 for Siena and Brescia as well as results from Chapter 6.a, Table 6.4 for China. Just to show the value of such comparison, car transport has an emergy demand around 1.74E+11 sej/p-km for the highway system Milan-Naples; in the range 1.66-2.47E+11 sej/p-km in Siena and Brescia; around 6.75E+11 sej/p-km in China, the latter showing a much lower efficiency.

Table 6.19. Inventory and emergy analyss of the Milan-Naples Highway passengers and commodity transport.

| | Unit | Annual Amount | Solar Transformity (seJ/unit) | Solar Emergy (seJ/year) |
|---|---|---|---|---|
| **Individual passenger transport (car)** | | | | |
| Steel of vehicles | kg/year | 7.04E+07 | 6.70E+12 | 4.72E+20 |
| Gasoline | J/ year | 2.52E+16 | 6.60E+04 | 1.66E+21 |
| diesel | J/ year | 3.52E+15 | 6.60E+04 | 2.32E+20 |
| LPG | J/ year | 8.72E+14 | 6.60E+04 | 5.75E+19 |
| Tires | J/ year | 1.50E+14 | 2.10E+04 | 3.14E+18 |
| Lubricant | J/ year | 1.10E+14 | 6.60E+04 | 7.23E+18 |
| Driving | J/ year | 3.98E+13 | 1.29E+07 | 5.14E+20 |
| Labor for vehicle maintenance | J/ year | 1.04E+11 | 1.29E+07 | 1.34E+18 |
| Vehicle cost | €/ year | 9.80E+08 | 1.30E+12 | 1.27E+21 |
| **Total Emergy for Passenger Transport** | | | seJ/yr | **4.22E+21** |
| **Commodity transport** | | | | |
| Steel of vehicles | kg/ year | 8.45E+06 | 6.70E+12 | 5.66E+19 |
| Gasoline | J/ year | 3.63E+15 | 6.60E+04 | 2.40E+20 |
| Diesel | J/ year | 2.89E+16 | 6.60E+04 | 1.91E+21 |
| Tires | J/ year | 7.75E+14 | 2.10E+04 | 1.63E+19 |
| Lubricant | J/ year | 2.07E+14 | 6.60E+04 | 1.37E+19 |
| Driving | J/ year | 1.78E+13 | 1.29E+07 | 2.30E+20 |
| Labor for vehicle maintenance | J/ year | 2.43E+13 | 1.29E+07 | 3.13E+20 |
| Vehicle cost | €/ year | 9.56E+07 | 1.30E+12 | 1.24E+20 |
| **Total Emergy for Commodity Transport** | | | seJ/yr | **2.90E+21** |
| Passenger traffic | | | 2.16E+10 | p-km/yr |
| Commodity traffic | | | 3.60E+10 | t-km/yr |
| Specific intensity for passengers (*) | | | 1.98E+11 | seJ/p-km |
| Specific intensity for commodities (*) | | | 1.25E+11 | seJ/t-km |

(*) Calculated intensities include a fraction of the emergy of infrastructures, from Table 6.17.

Table 6.20. Inventory and emergy analysis of the Milan-Naples High Speed Rail passengers and commodity transport.

| | Unit | Annual Amount | Solar Transformity (seJ/unit) | Solar Emergy (seJ/Year) |
|---|---|---|---|---|
| **Passenger transport** | | | | |
| Steel of vehicle | kg/ year | 1.74E+06 | 6.70E+12 | 1.16E+19 |
| Electricity | J/ year | 4.15E+15 | 1.50E+05 | 6.23E+20 |
| Service | €/ year | 7.35E+07 | 1.30E+12 | 9.55E+19 |
| Labor | J/ year | 5.77E+12 | 1.29E+07 | 7.45E+19 |
| **Total Emergy** | | | | **8.04E+20** |
| **Commodity transport** | | | | |
| Steel of vehicle | kg/ year | 4.39E+05 | 6.70E+12 | 2.94E+18 |
| Electricity | J/ year | 8.44E+14 | 1.50E+05 | 1.27E+20 |
| Service | €/ year | 2.85E+06 | 1.30E+12 | 3.71E+18 |
| Labor | J/ year | 4.78E+12 | 1.29E+07 | 6.17E+19 |
| **Total Emergy** | | | | **1.95E+20** |
| **Option 1: Maximum use rate(*)** | | | | |
| Passenger traffic | | | 1.52E+10 | p-km/yr |
| Commodity traffic | | | 5.48E+09 | t-km/yr |
| Specific intensity for passengers | | | 1.30E+11 | seJ/p-km |
| Specific intensity for commodities | | | 1.23E+12 | seJ/t-km |
| **Option 2: present use rate (*)** | | | | |
| Passenger traffic | | | 1.09E+10 | p-km/yr |
| Commodity traffic | | | 3.84E+10 | t-km/yr |
| Specific intensity for passengers | | | 1.84E+11 | seJ/p-km |
| Specific intensity for commodities | | | 1.75E+12 | seJ/t-km |

(*) Calculated intensities include a fraction of the emergy of infrastructures, from Table 6.18.

Table 6.21 Performance results for passenger and commodity transport by means of the different transportation modalities over the Milan-Naples axis.

| Transport modality | Load factor (passenger per trip) | Mass balance local scale (kg/p-km) | MFA global scale (kg/p-km) | Energy analysis local scale (MJ/p-km) | Energy analysis global scale (MJ/p-km) | Exergy analysis global scale (MJ/p-km) | Emergy analysis global scale ($10^{11}$ seJ/p-km) |
|---|---|---|---|---|---|---|---|
| Passenger transport | | | | | | | |
| Highway (car) | 1.8 | 0.13 | 0.53 | 1.37 | 1.87 | 1.31 | 1.74 |
| Highway (bus) | 50 | 0.03 | 0.11 | 0.24 | 0.33 | 0.25 | 0.24 |
| Railway[a] | 400–750 | 0.08–0.11 | 0.69–0.85 | 0.16–0.20 | 0.62–0.77 | 0.19–0.23 | 0.94–1.26 |
| HST/TAV[a] | 250–594 | 0.08–0.12 | 1.00–1.40 | 0.27–0.38 | 1.02–1.44 | 0.30–0.42 | 1.17–1.65 |
| | (tons per trip) | (kg/t-km) | (kg/t-km) | (MJ/t-km) | (MJ/t-km) | (MJ/t-km) | ($10^{11}$ seJ/t-km) |
| Commodity transport | | | | | | | |
| Highway | 8.79 | 0.18 | 0.60 | 0.91 | 1.25 | 1.01 | 1.08 |
| Railway[a] | 350–500 | 1.2–1.65 | 5.35–7.65 | 0.17–0.24 | 1.79–2.5 | 0.55–0.76 | 10.3–14.3 |
| HST/TAV Mi–Na[a] | 350–500 | 1.25–1.78 | 6.06–8.65 | 0.17–0.24 | 2.17–3.09 | 0.59–0.83 | 10.9–15.5 |

[a] Value range is referred to the current utilization rate of railway and the maximum theoretical load factor.

Table 6.22 shows the global scale emissions from the different modalities, allowing a comparison with Table 6.15 related to the emissions in the urban systems of Siena and Brescia. This allows, for example, an evaluation of the extent driving within an urban system affects emissions compared to driving outside of the city areas.

Table 6.22 Main global-scale emissions for the Milano-Napoli axis related to the investigated transport modalities.

| Transport modalities | $CO_2$ | CO | $NO_x$ | $PM_{10}$ | VOC | $SO_x$ |
|---|---|---|---|---|---|---|
| Passengers | | | | | | |
| Highway (cars) (kg/p-km) | $8.94 \times 10^{-2}$ | $6.68 \times 10^{-3}$ | 1.61E−03 | 6.94E−05 | $5.17 \times 10^{-4}$ | $2.38 \times 10^{-4}$ |
| Railway (kg/p-km) | $3.03 \times 10^{-2}$ | $7.56 \times 10^{-6}$ | $5.79 \times 10^{-5}$ | $1.46 \times 10^{-4}$ | $6.22 \times 10^{-7}$ | $3.39 \times 10^{-4}$ |
| HST/TAV (kg/p-km) | $4.82 \times 10^{-2}$ | $1.01 \times 10^{-5}$ | $8.87 \times 10^{-5}$ | $1.81 \times 10^{-4}$ | $7.92 \times 10^{-7}$ | $5.64 \times 10^{-4}$ |
| Highway (trucks) (kg/t-km) | $7.21 \times 10^{-2}$ | $9.03 \times 10^{-4}$ | $6.59 \times 10^{-4}$ | $6.41 \times 10^{-4}$ | $1.25 \times 10^{-4}$ | $2.06 \times 10^{-4}$ |
| Railway (kg/t-km) | $1.50 \times 10^{-1}$ | $1.09 \times 10^{-4}$ | $4.16 \times 10^{-4}$ | $2.11 \times 10^{-3}$ | $9.29 \times 10^{-6}$ | $8.55 \times 10^{-4}$ |
| HST/TAV (kg/t-km) | $1.89 \times 10^{-1}$ | $1.45 \times 10^{-4}$ | $5.36 \times 10^{-4}$ | $2.54 \times 10^{-3}$ | $1.18 \times 10^{-5}$ | $1.05 \times 10^{-3}$ |

*Exergy analysis and thermodynamic efficiency*

Exergy (a measure of work potential) could be better applied in order to calculate the thermodynamic efficiency of the engine/process and help identify existing bottlenecks and efficiency drops. Exergy is, by definition, a measure of maximum work obtainable in an ideal, reversible process (see Appendix). Since transport processes and tools are never ideal, the comparison of available work potential (exergy of fuel) and work actually obtained would indicate the so-called exergy loss, i.e., is the destruction of work potential due to irreversibilities occurring at system level (within the engine or due to the use of conversion tools that are not appropriate to the goal). In the case of transport processes/engines, it is impossible to assign an exergy content to the product (i.e., to the p-km or t-km supported) and therefore the exergy efficiency cannot be defined in the usual way. By the way, if the exergy efficiency is only calculated at the level of the engine (ratio of exergy delivered at the driving shaft to the exergy of the fuel), the indicator leaves the dynamics of the surrounding system (transport infrastructure) unaccounted for. A more flexible (and very telling) approach is the comparison of the actual exergy cost per unit of product (Jex/p-km) to the exergy cost calculated on the basis of the performance claimed by the vehicle constructors. We assume the latter as the upper limit to the vehicle performance, because constructors always advertise their cars with the best results they obtain in car tests. Such a comparison translates into the ratio of quasi-ideal (claimed) exergy costs, $Ex^*_{p\text{-}km}$ to real (system level) exergy cost, $Ex_{p\text{-}km}$:

$$\varepsilon = \frac{Ex^*_{p\text{-}km}}{Ex_{p\text{-}km}} = \frac{Ex_{min}}{Ex_{real}}$$

which provides a measure of how far the system-level performance, $Ex_{real}$, is from the engine-test performance, $Ex_{min}$, considered as the reference performance. Of course, accepting the constructor-claimed performance of the vehicle as reference performance makes the threshold very subjective and likely to change in the future,

thus requiring new calculations. However, the assumption does not affect the meaning of the present evaluation, which compares the actual exergy expenditures with the results theoretically achievable if the transport system does not add further sources of irreversibility to those already accounted for by the vehicle-test. In short, the smaller the ratio, the higher the improvement potential at system level.
For our calculation, we identified as $Ex_{min}$ the exergy performance (expressed as the minimum exergy required to move a p-km) of the best performing vehicle yet available on the market, running at maximum payload capacity, chosen from careful reading of vehicle specialized press.
Exreal is the actual average exergy requirement to move a p-km, calculated according to real data. Exergy associated to vehicle and infrastructure is not included in the accounting, so that the difference between Exmin and Exreal is only due to irreversibilities generated by traffic problems and transportation dynamics, driver behavior, state of the car, load factor, etc. Results are shown in Table 6.23.

Table 6.23 Second order efficiency of passenger transport on Milano–Napoli axis

| Transport modalities | $Ex_{min}$ (MJ/p-km) | ε (%) |
|---|---|---|
| Highway (car) | 0.42 | 21 |
| Highway (bus) | 0.29 | 95 |
| Railway[a] | 0.21 | 80–90 |
| TAV[a] | 0.21 | 57–80 |

[a]Higher and lower range value are referred to maximum and actual utilization rate, respectively.

Cars show an ε-value of 21% and this means that the 79% of exergy used by cars to move peoples is squandered for system-generated irreversibilities; this is mainly due to the fact that the medium load factor for car running on the highway is 1.8 persons per vehicle versus the 4 persons per vehicle used to calculate the reference value as well as to further sources of irreversibility generated by traffic dynamics. Load factor and people behavior are more important and relevant than specific vehicle fuel consumption:
this means that each technological improvement of engines will be made negligible if cars are still used as single-seat vehicles and if the driver does not adopt an appropriate driving behavior.
The higher ε-value for buses indicates that they are used closely to their claimed best performance; in this case, improvements aimed at exergy conservation can only be obtained by means of technological improvements.
Reference value for Inter-City and HST/TAV trains is assumed to be an electric train with a 4MW power locomotive: for Inter-City, the main reason of inefficiency is due to the lower load factor, while for HST/TAV inefficiencies are due both to the lower load capacity (594 versus 750 persons for trip) and higher power (8.8MW) of locomotives.
A ‘‘realistic’’ reference for commodity transportation is very difficult to identify

because the best option could be represented by the big road trucks with very high load capacity factor (more than 32 t per trip). This kind of trucks cannot be chosen as reference because they cannot be used for short distance or for inside-the-city transport, due to their encumbering size. On the other hand, small delivery vans can be used both for urban and extra-urban transport, but their exergetic performances comes out to be very bad because of their specific fuel consumption for ton transported; moreover, they cannot be compared with trains. Heavy trucks and small delivery vans cover, respectively, the 6% and 68% of vehicles used for commodity transport in Italy, in so identifying very distinct sub-sectors of the commodity transport sub-system. The only way to perform such a calculation would be to deal with trucks in the same way we did for cars (i.e., identifying the best claimed performance for each sub-sector, and so on). Since the procedure would not add any new insight to the previous results, we do not perform this last calculation.

*Discussion of results*

Specific energy consumption of vehicles is not always the most important factor affecting the choice of a transportation system. Other parameters, namely load factor of vehicles, power of engines appropriate to use, energy and material cost of infrastructures must be taken into proper account for environmentally sound transport policy making. Results are always space- and time-scale specific. When only localscale dynamics is investigated (e.g., direct fuel consumption), several important aspects are disregarded and results do not provide a comprehensive picture of the whole set of problems/constraints involved. When indirect energy and material costs are taken into account (MFA, EEA, EMA methods), the role of infrastructures as well as the impossibility of increasing the load factor of some of the modalities investigated (e.g., HST/TAV) heavily affect the performance indicators and raise several questions on the actual viability and improvement potential of some transportation patterns.

Things appear very different when the global energy and material requirement are accounted for, using the ''global scale approach'', in that two different new effects can be observed: (a) specific intensities show always higher values than expected; and (b) according to the infrastructure utilization rate, the same vehicle, running on different road or railway systems, may show very different performances. In fact, cars running on the highway show generally lower material and energy intensities than cars running on rural roads or city streets because of a higher load factor on the ''highway path'' and a more stable trip speed.

Results do not only suggest strategies based on improved engine performance (although the advantage of technical improvements cannot be denied), but strongly point out the need for appropriate use of each transport tool as well as the existence of material, energy and use constraints which cannot easily be removed and which should be taken into account for environmentally sound transport policy choices. A system view is needed, in order to look at the process under different aspects. The multi-method and multi-scale approach used in the investigation provides a clear understanding of the fact that a system cannot be investigated only at local or process scale (direct use of input flows) nor under a mono-dimensional point of view (energy demand) as none of the applied methods can be considered exhaustive in itself to define the best solution. For example, when only direct energy demand is accounted for, Table 6.21 suggests that electric Inter-City railway is by far the best way to transport people and commodities, which is in general the most common opinion. Instead, if the focus is placed on embodied energy instead of direct energy, the picture changes radically and indicates buses and trucks as the most appropriate tools. This is not because of an inherent higher suitability of the tool itself, but it is a direct consequence of the increased role of infrastructure and engine power required by the train system. Other large-scale methods (MFA, EMA) provide more or less the same results, with HST/TAV ranking very low and buses showing the best performance.

National and European regulations, eco-labels, local traffic restrictions and the whole debate around strategies for sustainable transport, are mainly focused only on the specific performances of the vehicles. Typical examples are the specific amount of different pollutants expressed as g/v-km (grams per vehicle transported over one km), which are the indicators on which the European eco-labels for road vehicles are based on. Since the final goal of transportation is not to move a vehicle over a certain distance, but to move passengers and goods, p-km and t-km, not v-km, should be the most appropriate reference units to better identify sustainable strategies. The paradoxical result is that CO2 emissions (similarly to other performance indicators) calculated as g/p-km for a modern and high efficiency car only carrying one passenger, will be always higher than those calculated for a 10-year-old car with two or three passenger on board. Policies should address the load-factor issue, not only low specific consumption of fuels (which does not include the issue of materials used as well as embodied energy, material and environmental costs) and encourage full-load use of vehicles. Moreover, improving the loading factor of cars and trucks is likely to lead to decreased number of circulating vehicles—in spite of rebound effect concerns–and in turn finally affecting total fuel use.

Time issue, meant as duration of trip, as well as travel comfort is not included in the present study. There is no doubt that a very comfortable car (e.g., SUV) with modern equipment and HST/TAV provide faster and more comfortable travel conditions. The problem here is twofold and would also deserve much higher attention from transport policy makers:

(a) The practical impossibility to use the infrastructure at higher load factor than described in this study places a higher limit to further time improvement and increased number of possible users, unless much higher resource investment is applied. As a consequence, faster and more comfortable transportation tools are and will be used by a minority of users. This is also due to high economic cost, which is in turn caused by higher energy, material and technological costs which are very unlikely to decrease at the present trend of increasing costs of fossil fuels, steel and copper in the international market.

(b) Implementing high embodied-resource modalities diverts energy, material and financial investments from less intensive patterns. The latter would provide maybe smaller benefits to a majority of users, but would translate into a much higher global benefit for society and environment. In times of declining cheap resource availability, the stability of a system relies more on the globality and effectiveness of the service provided than on high technological individual performances which leave the rest of the system unchanged.

## Appendix

Summary of the different methods used in this study.

*MFA—material flow accounting*

Quantifying input and output mass flows is a preliminary step. We need to assess not only the amount of input materials, but to the highest possible extent the amount of outputs (products, co-products, and emissions). The latter are important for the evaluation of the different possible kinds of environmental impact. In addition, when we expand our scale of investigation, we realize that each flow of matter supplied to a process has been extracted and processed elsewhere. Additional matter is moved from place to place, processed and then disposed of to supply each input to the process. Sometimes a huge amount of rock must be excavated per unit of metal or chemical element actually delivered to the user. Most of this rock is then returned to the mine site and the site reclaimed, but its stability is lost and several chemical compounds become soluble with rainwater and may affect the environment in unexpected ways. Accounting for the material directly and indirectly involved in the whole process chain has been suggested as a measure of environmental disturbance by the process itself. A quantitative measure is provided by means of material intensity factors (MIF) calculated for several categories of input matter, namely abiotic, biotic, water, and air. The total mass transfer supporting a process indirectly measures how the process affects the environment due to resource withdrawal.

*EEA—embodied energy analysis (also Cumulative Energy Demand)*

First-law heat accounting is very often believed to be a good measure of energy cost and system efficiency. The energy invested into the overall production process is no longer available. It has been used up and it is not contained in the final product. The actual energy content (measured as combustion enthalpy, HHV, LHV, etc.) of the product differs from the total input energy because of losses in many processes leading to the final product. Energy analysts refer to the total energy required in the form of crude oil equivalent as to ''embodied energy''. In general, EEA accounts for the total amount of commercial energy (mainly fossil fuels or equivalent energy) expressed in terms of gram oil equivalent or MJ. Energy Intensity is the amount of raw oil (g or MJ) needed per unit of product.

*EXA—exergy analysis*

Not all forms of energy are equivalent with respect to their ability to produce useful work. While heat is conserved, its ability to support a transformation process must decrease according to the second law of thermodynamics (increasing entropy). This is very often neglected when calculating efficiency based only on input and output heat flows (first-law efficiency) and leads to an avoidable waste of still usable energy and to erroneous efficiency estimates. The ability of resources to supply useful work or to support a further transformation process must be taken into account and offers opportunities for inside-the-process optimization procedures, recycle of still usable flows, and downstream allocation of usable resource flows to another process. The ability of driving a transformation process and, as a special case, producing mechanical work, may be quantified by means of the exergy concept. According to Szargut et al. [Szargut J, Morris DR, Steward FR. Exergy analysis of thermal, chemical and metallurgical processes. London: Hemisphere Publishing Corporation; 1988.] exergy is ‘‘the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the abovementioned components of nature’’. Chemical exergy is the most significant free energy source in most processes. Szargut calculated chemical exergy as the Gibbs free energy relative to average physical and chemical parameters of the environment. By definition, the exergy (ability of doing reversible work) is not conserved in a process: the total exergy of inputs equals the total exergy of outputs (including waste products) plus all the exergy losses due to irreversibility. Quantifying such exergy losses (which depend on deviations from an ideal, reversible case) for a process offers a way to calculate how much of the resource and economic cost of a product can be ascribed to the irreversibility affecting the specific technological device that is used as well as to figure out possible process improvements and optimization procedures aimed at decreasing exergy losses in the form of waste materials and heat. Exergy losses due to irreversibilities in a process are very often referred to as ‘‘destruction of exergy.’’ Exergy efficiency is therefore defined as the ratio of the exergy of the final product to the exergy of input flows.

*EMA – EMergy Accounting*

The same product may be generated via different production pathways and with different resource demand, depending on the technology used and other factors, such as boundary conditions that may vary from case to case and process irreversibility. In its turn, a given resource may require a larger environmental work than others for its production by nature. As a development of these ideas, H.T. Odum introduced the concept of emergy, i.e., ‘‘the total amount of available energy (exergy) of one kind (usually solar) that is directly or indirectly required to make a given product or to support a given flow’’. In some way, this concept of embodiment supports the idea that something has a value according to what was invested into making it. This way of accounting for required inputs over a hierarchy of levels might be called a ‘‘donor system of value’’, while EXA and economic evaluation are ‘‘receiver systems of value’’, i.e., something has a value according to its usefulness to the end user. Solar emergy was therefore suggested as a measure of the total environmental support to all kinds of processes in the biosphere, including economies. Flows that are not from solar source (like deep heat and gravitational potential) are expressed as solar equivalent energy by means of suitable transformation coefficients. The amount of input emergy dissipated per unit output exergy is called solar transformity. The latter can be considered a ‘‘quality’’ factor which functions as a measure of the intensity of biosphere support to the product under study. The total solar emergy of a product may be calculated as: (solar emergy) = (exergy of the product) * (solar transformity). Solar emergy is usually measured in solar emergy joules (seJ), while the unit for solar transformity is solar emergy joules per joule of product (seJ/J). Sometimes emergy per unit mass of product or emergy per unit of currency are also used (seJ/g, seJ/$, etc.). In doing so, all kinds of flows to a system are expressed in the same unit (seJ of solar emergy) and have a built-in quality factor to account for the conversion of input flows through the biosphere hierarchy. Values of transformities are available in the scientific literature on emergy. When a large set of transformities is available, other natural and economic processes can be evaluated by calculating input flows, throughput flows, storages within the system, and final products in emergy units. As a result of this procedure, a set of indices and ratios suitable for policymaking can be calculated.

# CHAPTER 7 – ELECTRIC AND ELECTRONIC WASTE MANAGEMENT AND RECYCLING

The amount of electric and electronic devices is growing exponentially worldwide, generating problems of huge demand of materials and energy as well as disposal aspects and pollution risks.

**Computers**

The number of Personal Computers (PC) used worldwide has grown exponentially in a very short time, from their first appearance to the most modern and sophisticated versions. PCs have become much needed elements for work activities as well as for private use. The useful life of a PC, in line with other electrical and electronic equipment, is relatively short, being on average about 4 years although they may last much longer if carefully maintained and equipped with suitable software consistent with their technical characteristics. Most often, short life is not only due to the actual wear of the components but to the market dynamics, that almost force to a fast replacement of equipment considered "obsolete", in order to keep pace with technological progress (in many cases we may talk of "planned obsolescence"). Estimates show that global computer e-waste will triple by 2025 (Dwivedy *et al.*, 2010). By 2016, this growth will lead to more computer e-waste generated in developing countries than in developed ones (Namias, 2013).

**Photovoltaic modules**

In recent years, photovoltaic (PV) systems have gained worldwide recognition and popularity as an environmentally friendly way of solving energy problems. However, the problem of PV panels decommissioning at the end of their useful life is yet to be suitably solved. Panels are expected/designed to last about 30 years (Fthenakis et al., 2011), and then will have to be decommissioned and disposed or re-used in some ways, not to further contribute to the huge problems of untreated waste. Considering the fast growth of the PV market (EPIA, 2014), and the related end-of-life (EoL) environmental issues, European Union calls for a long-term sustainability of the PV industry. According to McDonald and Pearce (2010), the amount of PV waste to be handled and disposed of is expected to grow drastically after 2030. In 2008, the amount of PV waste generated in the EU was around 3,800 tons and by 2030, this is expected to rise up to 130,000 tons (Larsen, 2009). One of the major concerns regarding the PV EoL treatment and disposal is the emission of hazardous metals, as chromium and lead, and toxic gases, as hydrofluoric acid, that may be discharged to the environment if special requirements for their handling and disposal are not adopted (Fthenakis, 2003).

**WEEE**

Both computers and PV modules, due to their technical complexity, are subject to a special end-of-life management and fall into the type of waste called WEEE (Waste Electrical and Electronic Equipment). Indeed, decommissioned PV panels are included, for the first time, in the list of waste electrical and electronic equipment

(WEEE) in the EU Directive 2012/19/EC. Challenges faced by WEEE management are not only consequences of growing quantities of e-waste but also of the complexity of WEEE types; this waste category is one of the most complex waste streams due to both the wide variety of commercial products, from mechanical devices to highly integrated systems, and to fast technological innovation trends (Ylä-Mella *et al.*, 2004). As a consequence of WEEE's complexity, the European Union (EU) has designed a large number of Directives for regulation and management: both in terms of restrictions on the use of hazardous substances in EEE (Electric Electronic Equipment) and promotion of collection and recycling of obsolete equipment (2002/95/EU, 2002/96/EU, respectively). Despite these directives have been transferred and integrated into the legal body of EU countries, only one-third of WEEE in Europe is collected, separated and adequately treated. The EU collects about 33 percent of e-waste destined to environmentally sound treatment processes, while most of the other two-thirds is potentially still going to landfills and to sub-standard treatment sites in Europe or outside, via illegal exports pathways (European Commission / Recast of the WEEE Directive, 2011). This figure means around 3.3 million tons treated out of the 9.5 million tons to be disposed of annually in Europe. Moreover, thanks to the rapid development of information technology, hardware and software of the computers are updated very quickly, which translates into a fast WEEE increase in recent years.

**A challenge of resource mining. Material and energy efficiency.**

An important aspect of this typology of waste, considering the context of economic crisis and rising prices of raw materials, is that they are also a valuable "mine" of industrial materials that, if properly exploited, can be re-introduced into the production chains with considerable economic advantages and, above all, accompanied by a decreasing environmental burden. Therefore, a more efficient use of resources would translate into combined advantages for the environment and economic growth opportunities. WEEE exporting countries are also losing a significant amount of resources, such as rare earth metals, copper and gold, which makes recycling, even more important. One of the biggest obstacles to WEEE recycling is still represented by the lack of consumer awareness about the potential economic and environmental benefits that can be obtained by implementing electronic waste recycling activities, in so leading to a more sustainable society (Tanskanen, 2013). Concerning the efficiency of WEEE recycling, we should not think that all the problems are technical nor that all technical problems have already been solved: there are problems related to political, legislative and economic aspects, as well as to society and culture. A new perception is slowly emerging, in which waste, if appropriately managed, becomes a valuable resource that could ultimately contribute to a more environmentally sustainable society, thus preventing the extraction of virgin materials thanks to reuse or recycling, and replacing fossil energy sources via energy recovery and implementation of renewable energies. This is likely to help reducing both local and global environmental impacts.

This study explores the material and energy efficiency of production, use and recovery of electric and electronic equipment, focusing on the following cases:

*Chapter 7.a Energy and eMergy evaluation of production and operation of a personal computer. Focusing on advantages of recycling.*

*Chapter 7.b Life Cycle Assessment of a recycling process for crystalline silicon photovoltaic panels end-of-life*

## CHAPTER 7.a Energy and eMergy evaluation of production and operation of a personal computer

*Introduction*

This section deals with the energy and environmental performance indicators of the production, operation and recycling phases of a laptop and a desktop computer. Assumptions are made about the use of virgin materials and fossil-based electricity, to be compared with the use of recycled materials and renewable electricity all over the life cycle of the investigated computers. Environmental costs are assessed by means of selected energy, eMergy and LCA indicators.

*Materials and Methods*

Focus is firstly placed on energy and material production costs and energy and material savings that can be achieved if recycled materials from WEEE treatment are feedback to the supply chain for new PC production. Then, the energy and environmental burden generated over a 5 year operative life are also calculated and compared. The two investigated computers are:

- Desktop: 2009 Olidata with Asus M2N-MX SE PLUS's motherboard, AMD Athlon(TM) II X2 245' s CPU and Maxtor 250 GB's HHD, and
- Laptop: Sony Vaio VGN-FZ31M with MBX-165's motherboard**,** Intel Core 2 Duo's CPU and T7250 and *SATA 200 GB's HHD.*

These two obsolete PCs were fully shredded into their functional components (case, ram, motherboard, monitor, power unit, etc.) and then into their constituent materials (iron, plastic, copper, etc.) when possible, and micro-components (capacitors, chips, resistances, etc.). In so doing, inventories of functional components as well as of materials and micro-components where listed, to serve as the starting point of energy and eMergy analyses. Since micro-components still are composite devices that could not be further shredded, and their production, in turn, requires an upstream industrial process chain, their related energy and material flows were taken from processes available in the Ecoinvent database, adjusted according to the actual size of the investigated computers. The production phase also involves the assembly of components, which entails additional energy inputs, found in published literature and technical reports. The latter also includes transport of raw materials to the manufacturing sites, while instead the transport of computers to the final user is not included.

The study investigates two scenarios:

- Production of desktop and laptop PCs using virgin materials and non-renewable energy (for electricity and heat); Business-as-Usual (BAU) scenario;
- Production of desktop and laptop PCs using recycled materials and renewable electricity and heat sources; use of 100% renewable electricity (mix of photovoltaic, wind, geothermal and hydro-electricity (Terna S.p.A. and the Terna Group, 2014) in proportion to the Italian electricity mix, ENEL Green Power Co (Enel Green Power, 2016); Recycling and Renewables (RAR) scenario.

Production scenarios are then integrated with use scenarios, with additional assumptions on the number of operative hours, hours in standby, and hours in which the computers are switched off.

Figure 1 provides a system diagram of input and output material and energy flows contributing to a generic PC production process. The diagram is intended as the start of the inventory phase, for both input and output flows. Renewable and non-renewable energy and material flows are shown to cross the boundary of the system and provide support to the background and foreground processes that convert resources into a manufactured product. Some inflows are provided for free by nature, while others are imported from the main economic system in which the investigated process is embedded, also including inflows of labor and services. These inflows of labor and services are not accounted for in conventional energy accounting (E.E.A., Embodied Energy Analysis, or C.E.D., Cumulative Energy Demand), while instead they are most often included in the Emergy approach as an important part of the accounting. Within the process boundary of Figure 1, assumed to indicate a regional scale, the industrial steps converting raw resources into manufactured components and then into assembled computers within the computer industry are shown. Emissions and waste materials that are not captured by the industrial end-of-pipe devices (e.g., scrubbers) are shown to be released to the local atmosphere and diluted by wind, rain and other environmental services. The surrounding ecosystem provides land occupation possibility, construction materials and minerals, and other supporting services (cooling, insolation, etc) to the entire production chain.

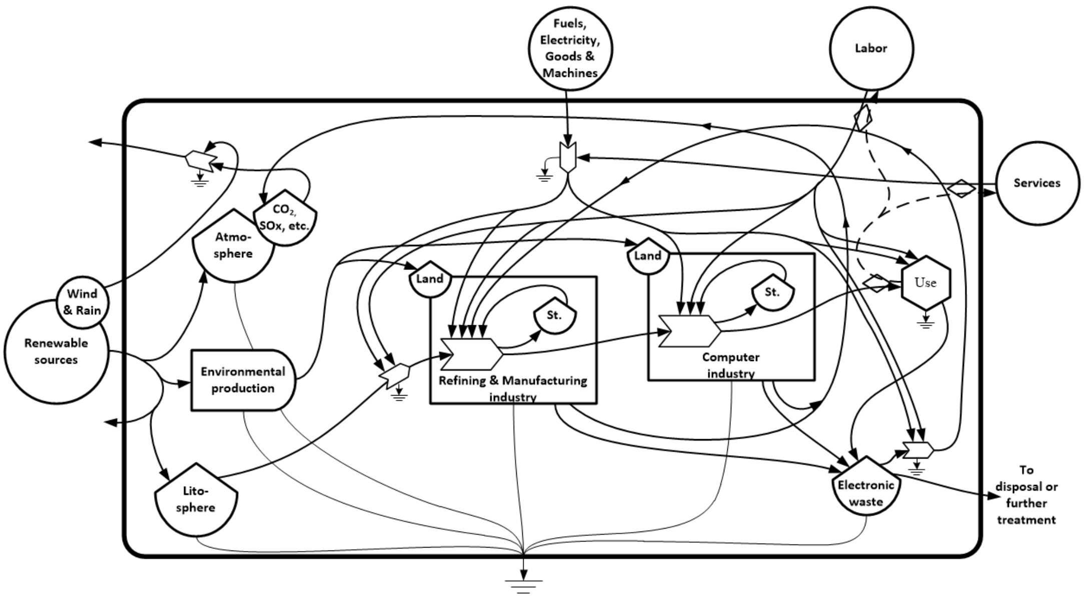



**Figure 1.** System Diagram of PC's production, showing energy and material flows (energy systems symbols from Odum, 1996), according to the keys below.

Table 1 lists, as a preliminary inventory, the main functional components of the two investigated computers, while Fig. 2 provides an aggregate inventory of the main materials that were used directly and indirectly in all the steps of the production process.

**Table 1.** Inventory of main Computer's components

| Inventory | *Desktop PC (g)* | *Laptop PC (g)* |
|---|---|---|
| | | |
| Blu-ray/DVD/CD Players | 8.62E+02 | 1.71E+02 |
| Keyboard | 7.37E+02 | 1.02E+02 |
| Screws and bolts | 4.33E+01 | 5.50E+01 |
| Motherboard | 8.22E+02 | 2.54E+02 |
| Battery | n.a. | 3.30E+02 |
| Motherboard Speaker | 3.30E+01 | 1.49E+01 |
| HDD | 3.86E+02 | 9.70E+01 |
| Case | 5.01E+03 | 5.14E+02 |
| Monitor | 4.30E+03 | 8.51E+02 |
| Power Supply | 8.43E+02 | 357E+02 |
| Cable | 3.99E+02 | 2.05E+02 |
| Mouse | 9.25E+01 | n.a. |
| | | |
| **Total weight (g)** | **1.35E+04** | **2.95E+03** |

n.a.= not applicable

*Embodied Energy Analysis (EEA)*

E.E.A. (also referred to as Cumulative Energy demand, C.E.D.) (Frischknecht *et al*., 2015) can be defined as the process of determining the energy (free energy in thermodynamics terms) required directly and indirectly to allow a system to produce a specified good or service (Slesser, 1974). It accounts, basically, for the energy used for the production and refinement of fuels, electricity, fertilizers, and other goods or chemicals, in terms of fossil oil equivalents requested to produce them (Franzese *et al*., 2009). The most important result of the embodied energy analysis is the assessment of the total amount of oil equivalents that cross the system's boundaries (as input) with reference to the final product, expressed by its mass value, or number of pieces or energy value (output).

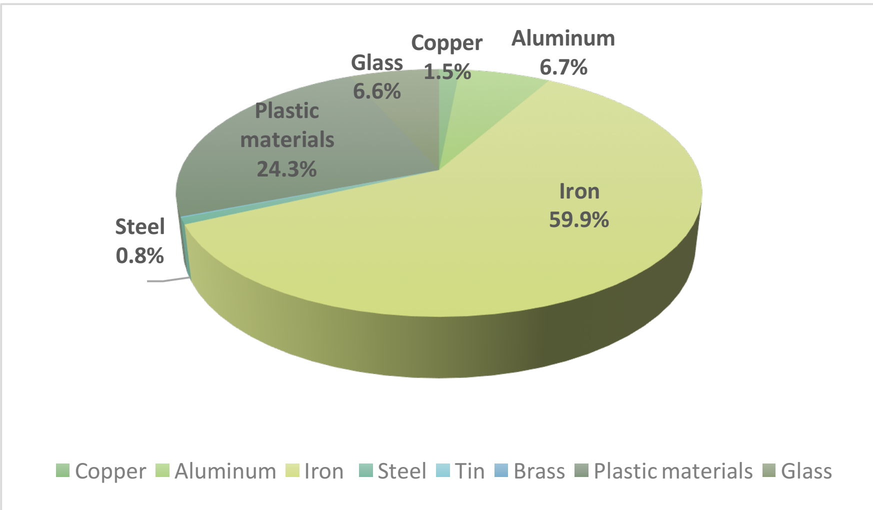



**Figure 2.** Inventory of main primary materials within a desktop PC

Tables 2a and 2b show the life-cycle energy intensities of the main primary materials used for computer production, also showing the slight difference existing between ingot (Hammond *et al*., 2008) and refined material (Weidema *et al*., 2013). Values include the energy for extraction and first refining as well as all of the energy consumed until the product has reached the point where it is manufactured into a computer component. This means extraction, refining and transportation.

**Table 2.** Energy intensities of basic materials used in PC production

| (a) Ingot | |
|---|---|
| **Items** | **MJ/kg** |
| Copper | 57 |
| Aluminium | 150 |
| Iron | 25 |
| Steel | 35 |
| Tin | 250 |
| Brass | 44 |
| Glass | 20 |
| Plastic | 80 |
| *energy intensities from Hammond et al., (2008) | |

| (b) Refined | |
|---|---|
| **Items** | **MJ/kg** |
| Copper | 60 |
| Aluminium | 161 |
| Iron | 48 |
| Steel | 101 |
| Tin | 345 |
| Brass | 68 |
| Glass | 20 |
| Plastic | 100 |
| *energy intensities from Weidema et al., (2013) | |

Values from Tables 2a and 2b for energy intensities of material flows are used in order to calculate the cumulative energy costs of production and use of the investigated desktop and laptop computers, in a BAU scenario. The inventories used for calculation are listed in Table 3 (laptop computer) and Table A1 (Appendix, desktop computer). A similar evaluation is performed in the same Tables, under RAR scenario. In addition to the energy intensities of pure metals and minerals from Table 2a and 2b, the energy intensities of micro-components (e.g. battery, capacitors, microchips, etc.) made with primary materials were taken from the production chain of these components in the Ecoinvent database, with some specific adjustments to size and typology. Instead, the energy intensities of micro-components made with recycled materials and renewable energy were estimated from the same Ecoinvent database, replacing the energy intensities of primary materials and fossil powered electricity by means of the energy intensities of recycled materials (Hammond et al., 2008) and "green electric mix" of the Italian electric Company ENEL Green Power (Enel Green Power, 2016).

*Emergy accounting*

Emergy analysis, as an evaluation method (Odum, 1996; Brown and Ulgiati, 2004), can be used to explore the interactions between production and consumption processes and the environment where resources used by the process come from. Emergy is the amount of available energy that is required, directly or indirectly, to generate a given flow or storage of energy or matter output, expressed in units of one kind (usually solar).

*Results*

*Energy costs of production*

Most of computer's companies use metals and plastics made with virgin materials and processed by means of grid electricity, most often powered by fossil sources (assumption A, business-as-usual framework, BAU). Starting from the computer assembly and going back to production of components, it is therefore possible to calculate the energy and environmental costs of computer production and operation. This would provide an upper limit to production and consumption burdens. In a like manner, assuming a production process that uses recycled materials and renewable electricity to the largest possible extent consistent with the present technical know-how (assumption B, recycling and renewable scenario, RAR), much lower energy and environmental costs can be calculated, to set a lower limit to production and consumption impacts.
For instance, recycled ("secondary") aluminium has 90% less embodied energy than virgin ("primary") aluminium (Grimes *et al.*, 2008), which may determine much lower energy and environmental costs. Of course, considering technical obstacles to full recycling of resources, the calculated thresholds are only indicative of the improvement potential associated to recycling and renewable electricity, not to talk of yet unforeseeable progresses from technological innovation.
The energy used for the desktop PC assembly is estimated as 51 kWh plus 5 kWh for packaging (Williams, 2004), whereas the laptop PC requires an assembly input energy around 43 kWh, packaging included (Jönbrink *et al.*, 2007). The total energy for production is estimated in Table 4 as about 43 and 11 kg oil equivalent for the laptop PC respectively under the BAU and RAR scenarios; similarly, it is about 58 and 14 kg oil equivalent for the desktop PC, under the same assumptions (Table A1, Appendix). It should be noted that the lower fossil energy consumption in the case of processes using recycled materials and renewable energies does not mean a lower total energy cost of the product, but instead a lower use of fossil energy. Manufacturing a computer requires the same amount of energy in all cases, but a much smaller fraction of fossil energy.

*Energy cost of use phase*

The use phase energy demand was assessed under the same BAU and RAR frameworks, but additional assumptions were made about a computer's average operative life. In particular, the assumption is made that the actual computer operative time is five hours per day, with a standby mode of 2 hours and 17 hours off, 365 days per year. Weekends and holidays are also included, considering computers to be not only a work tool, but also a tool for daily life (internet, leisure, shopping, etc.). Based on these assumptions, we calculated 5-year electricity consumption of 226 and 515 kWh, for a laptop and desktop PC, respectively. Under the BAU and RAR assumptions, generating the electricity to power the computers requires different amounts of fossil energy, since RAR is mainly powered by renewables and only a small, unavoidable fraction of fossil energy is accounted for, translating into 46 and 1.6 kg oil equivalent respectively for the laptop PC (Table 3) as well as 103 and 3 kg oil equivalent respectively for a desktop PC (Table A1, Appendix).

*$CO_2$ emissions*

The GHG emissions associated to the production of the investigated computers were first estimated based on the combustion reaction stoichiometry, yielding a conversion factor around 3.2 kg $CO_2$-eq. per kg of oil equivalent used (average from the combustion of coal, oil, and natural gas in electricity production plants in Italy, also considering the average efficiency of the different typologies of power plants); this value was double-checked by means of the software OpenLCA, based on the database Ecoinvent v3.01 and the impact assessment method ReCiPe Midpoint H (Goedkoop *et al*., 2009), where a 14% larger global warming potential GWP around 3.64 kg $CO_2$-eq. per kg of oil equivalent was computed. The larger value yielded by a full LCA GWP calculation provides a way to ascertain which fraction of the total fossil energy demand occurs in the form of fossil fuels burned directly (mainly for transport, heat demand) over the entire production chain instead of being used for electricity production. In fact, a part from the electricity used for assembly, smaller fractions of energy are used for the production of refined materials and manufacture of micro-components. The lower efficiency associated to the direct combustion of fuels in earlier steps is likely to translate into higher $CO_2$ emissions, as suggested by the LCA GWP calculated, thus calling for further increased efficiency also in the upstream process steps. In the following of this study we will, however, keep the conservative estimate of 3.2 kg $CO_2$-eq. per kg of oil equivalent used.
The total oil equivalent consumption for production and 5-year operation of the laptop and desktop PCs is multiplied by the calculated conversion factors to yield the $CO_2$ emissions reported in Tables 3 and A1.

*Emergy costs of PC production*

The emergy associated to each input flow can be computed, for both production and use phases of laptop and desktop PCs. In so doing, the work of nature in the earth crust and the work of humans in technological cycles are both accounted for and translated into the emergy associated to each inflow to the process in a BAU scenario. The RAR option is addressed by reminding the emergy algebra, that dictates that the emergy of recycled flows is not added to the total emergy driving the process and only the emergy for collection and actual recycling must be included (Bala Gala et al., 2015). As a result, the recycled materials are computed in the assessment without attributing them any extraction and refining energy costs. Of course, the costs for re-processing of the recycled material into the final component are considered instead, because they are afforded every time the production process for each component occurs again.

**Table 3.** Embodied Energy Analysis of the production and operation of a laptop PC

| Laptop PC | | Using primary materials and nonrenewable electricity mix | | Using secondary materials and renewable electricity mix | |
|---|---|---|---|---|---|
| Inventory | Raw Amount (g)* | Energy intensity (MJ/g)* | Embodied Energy (MJ) | Energy intensity (MJ/g)* | Embodied Energy (MJ) |
| **Materials** | | | | | |
| Copper | 65.21 | 0.06 | 3.84 | 0.02 | 1.04 |
| Aluminum | 414.77 | 0.16 | 66.69 | 0.03 | 12.03 |
| Iron | 287.5 | 0.05 | 13.74 | 0.01 | 1.44 |
| Steel | 97.3 | 0.1 | 9.84 | 0.01 | 0.88 |
| Tin | 1.1 | 0.34 | 0.38 | 0.05 | 0.05 |
| Brass | 39.51 | 0.07 | 2.67 | 0.04 | 1.74 |
| Plastic materials | 616.69 | 0.1 | 61.67 | 0.03 | 19.73 |
| Glass | 255.4 | 0.02 | 5.11 | 0.01 | 2.81 |
| **Microcomponents** | | | | | |
| Internal clock nickel battery | 3 | 0.26 | 0.78 | 0.08 | 0.24 |
| Capacitors | 30.1 | 0.44 | 13.11 | 0.2 | 6.05 |
| Inductors | 35.35 | 0.12 | 4.32 | 0.1 | 3.48 |
| Led | 0.37 | 16.81 | 6.22 | 15.77 | 5.84 |
| Microchips | 25.7 | 6.2 | 159.3 | 2.98 | 76.49 |
| Printed Wiring Board | 297 | 2.78 | 825.66 | 0.86 | 256.52 |
| Cables | 205 | 0.11 | 21.55 | 0.04 | 7.22 |
| Diodes | 8 | 9.45 | 75.59 | 1.93 | 15.45 |
| Dynamo | 32 | 0.07 | 2.21 | 0.02 | 0.52 |
| Resistances | 2.17 | 0.44 | 0.95 | 0.02 | 0.05 |
| Reflecting glass surfaces | 43.2 | 0.02 | 0.86 | 0.01 | 0.48 |
| Polarizers | 27.63 | 0.02 | 0.55 | 0.01 | 0.28 |
| Transistors | 24.13 | 0.35 | 8.56 | 0.04 | 0.96 |
| Connectors | 33.71 | 0.06 | 2.19 | 0.03 | 0.86 |
| Alloys | 50 | 0.08 | 4 | 0.03 | 1.5 |
| Magnets | 33.11 | 0.05 | 1.58 | 0.01 | 0.17 |
| Lithium battery | 282 | 0.44 | 124.34 | 0.14 | 39.98 |
| Miscellaneous materials | 40 | 0.35 | 14 | 0.12 | 4.8 |
| **Assembly** | | | | | |
| Electricity for assembly (kWh)* | 43 | 8.57 | 368,51 | 0,29 | 12.43 |
| **Final product** | | | | | |
| Mass of assembled computer (g) | 2949.95 | | | | |
| Cumulative energy demand (MJ) | | | 1798,24 | | 468.21 |
| Oil equivalent (kg)* | | | 42.82 | | 11.15 |
| **Five year operation** | | | | | |
| Electricity for 5 year operation (kWh)* | 226 | 8.57 | 1936.82 | 0.29 | 65.54 |
| Oil equivalent (kg)* | | | 46.11 | | 1.56 |
| **$CO_2$ emissions (production and five year operation)** | | | | | |

| | Conversion factor ($kg_{CO2\ eq}/kg_{oil\ eq}$) | $CO_2$ release ($kg_{CO2\ eq}$) | Conversion factor ($kg_{CO2\ eq}/kg_{oil\ eq}$) | $CO_2$ release ($kg_{CO2\ eq}$) |
|---|---|---|---|---|
| **Total $CO_2$ equiv emission** | 3.2 | 284.6 | 3.2 | 40.7 |

* Unit of electricity input flow is kWh; unit of energy intensity of electricity is MJ/kWh; unit of oil equivalent is kg.

Finally, also the operation step of both computers is accounted for, in terms of electricity use under both BAU and RAR assumptions, for five-year lifetime. The UEVs of electricity inflows are computed as Italian fossil powered electricity and green Italian electric mix, by means of weighted averages of individual electricity production from each fossil or renewable source (Brown *et al.*, 2012; Brown & Ulgiati, 2002), whereas the percentages of energy sources in both mixes were obtained from Terna Group (2014).

Although in general emergy evaluations also include the emergy supporting Labor and Services, as previously explained in Section 2.3, we have not computed them in this study, limiting our assessment to the emergy of raw and manufactured resources. In fact, L&S depend on the economic system where the process occurs. Due to the generality of our goal, we prefer not to introduce a component that may become a source of large uncertainty. Results are shown in Tables 4 and A2.
Figure 3 shows the dominance of electricity for assembly as well as a few basic materials and micro-components such as aluminium, plastic, printed wiring board, connectors and lithium battery, in the BAU compared to RAR scenario (electricity for the use phase is not included). The decreased emergy demand for the same items in the RAR scenario clearly suggests where efforts should be directed if the goal is to improve the sustainability and environmental friendliness of computer production under the point of view of resource availability.

*Discussion*

The cumulative energy consumption, $CO_2$ emissions and emergy investment for the construction and use phases of the investigated computers under BAU and RAR assumptions (Tables 3, 4, A1 and A2) are indeed useful extensive indicators to be considered as reference values for future performance improvement of production and use processes. They provide an immediate measure of potential savings from the implementation of the RAR instead of the BAU option. For example, the fossil energy demand for the construction of a laptop PC is 1798 MJ in the BAU scenario while it is 468 MJ under the RAR assumption, with a potential 74% of fossil energy savings (Figure 4). A similar performance is also found in the case of the desktop PC (Table A1, Appendix). If we look more carefully into the data of Table 3, we realize that out of the total fossil savings of 1330 MJ, 356 MJ (27% of savings) are due to the replacement of fossil energy by means of renewable energy, while 974 MJ (73%) can be attributed to increased process efficiency achieved thanks to material recycling (i.e., lower energy expenditure over the material extraction and processing).

**Table 4.** Emergy analysis of the production and operation of a laptop PC

| Laptop PC | | Using primary materials and nonrenewable electricity mix | | Using secondary materials and renewable electricity mix | |
|---|---|---|---|---|---|
| **Inventory** | **Raw Amount (g)*** | **UEV (sej/g)*** | **Emergy (sej)** | **UEV (sej/g)*** | **Emergy (sej)** |
| **Materials** | | | | | |
| Copper | 6.52E+01 | 1.07E+11 | 6.97E+12 | 8.88E+09 | 5.79E+11 |
| Aluminum | 4.15E+02 | 5.09E+10 | 2.11E+13 | 2.39E+10 | 9.91E+12 |
| Iron | 2.88E+02 | 1.28E+10 | 3.68E+12 | 7.40E+09 | 2.13E+12 |
| Steel | 9.73E+01 | 2.07E+10 | 2.01E+12 | 1.91E+10 | 1.86E+12 |
| Tin | 1.10E+00 | 1.75E+12 | 1.92E+12 | 5.00E+10 | 5.49E+10 |
| Brass | 3.95E+01 | 1.20E+10 | 4.74E+11 | 1.04E+10 | 4.11E+11 |
| Plastic materials | 6.17E+02 | 2.97E+10 | 1.83E+13 | 1.48E+10 | 9.13E+12 |
| Glass | 2.55E+02 | 4.56E+09 | 1.16E+12 | 2.96E+09 | 7.56E+11 |
| **Microcomponents** | | | | | |
| Internal clock nickel battery | 3.00E+00 | 2.38E+11 | 7.15E+11 | 3.85E+10 | 1.15E+11 |
| Capacitors | 3.01E+01 | 5.32E+10 | 1.60E+12 | 4.03E+07 | 1.21E+09 |
| Inductors | 3.54E+01 | 9.03E+09 | 3.19E+11 | 5.51E+08 | 1.95E+10 |
| Led | 3.70E-01 | 2.19E+10 | 8.11E+09 | 1.31E+08 | 4.84E+07 |
| Microchips | 2.57E+01 | 2.39E+11 | 6.14E+12 | 6.60E+08 | 1.70E+10 |
| Printed Wiring Board | 2.97E+02 | 4.90E+10 | 1.46E+13 | 5.65E+08 | 1.68E+11 |
| Cables | 2.05E+02 | 7.49E+09 | 1.54E+12 | 3.25E+09 | 6.66E+11 |
| Diodes | 8.00E+00 | 4.74E+10 | 3.79E+11 | 8.91E+08 | 7.13E+09 |
| Dynamo | 3.20E+01 | 4.74E+10 | 1.52E+12 | 5.87E+08 | 1.88E+10 |
| Resistances | 2.17E+00 | 1.13E+08 | 2.45E+08 | 4.85E+06 | 1.05E+07 |
| Reflecting glass surfaces | 4.32E+01 | 2.67E+10 | 1.16E+12 | 1.65E+07 | 7.13E+08 |
| Polarizers | 2.76E+01 | 2.67E+10 | 7.39E+11 | 1.99E+08 | 5.50E+09 |
| Transistors | 2.41E+01 | 2.25E+10 | 5.43E+11 | 3.22E+08 | 7.76E+09 |
| Connectors | 3.37E+01 | 2.57E+11 | 8.66E+12 | 1.61E+08 | 5.42E+09 |
| Alloys | 5.00E+01 | 1.00E+10 | 5.00E+11 | 3.00E+09 | 1.50E+11 |
| Magnets | 3.31E+01 | 9.10E+09 | 3.01E+11 | 2.56E+06 | 8.48E+07 |
| Lithium battery | 2.82E+02 | 4.68E+10 | 1.32E+13 | 3.31E+10 | 9.33E+12 |
| Miscellaneous materials | 4.00E+01 | 1.00E+10 | 4.00E+11 | 3.00E+09 | 1.20E+11 |
| **Assembly** | | | | | |
| Electricity for assembly (kWh)* | 43 | 1.89E+12 | 8.14E+13 | 2.58E+11 | 1.11E+13 |
| **Final product** | | | | | |
| Mass of assembled computer (g) | 2.95E+03 | | | | |
| Total emergy of production (sej) | | | 1.89E+14 | | 4.65E+13 |
| UEV of PC (sej/g) | | 6.42E+10 | | 2.28E+10 | |
| **Five year operation** | | | | | |
| Electricity for 5 year operation (kWh)* | 226 | 1.89E+12 | 4.28E+14 | 2.58E+11 | 5.83E+13 |
| Total emergy of production and operation (sej) | | | 6.17E+14 | | 1.05E+14 |

* Unit of electricity input flow is kWh; therefore, unit of UEV of electricity is sej/kWh

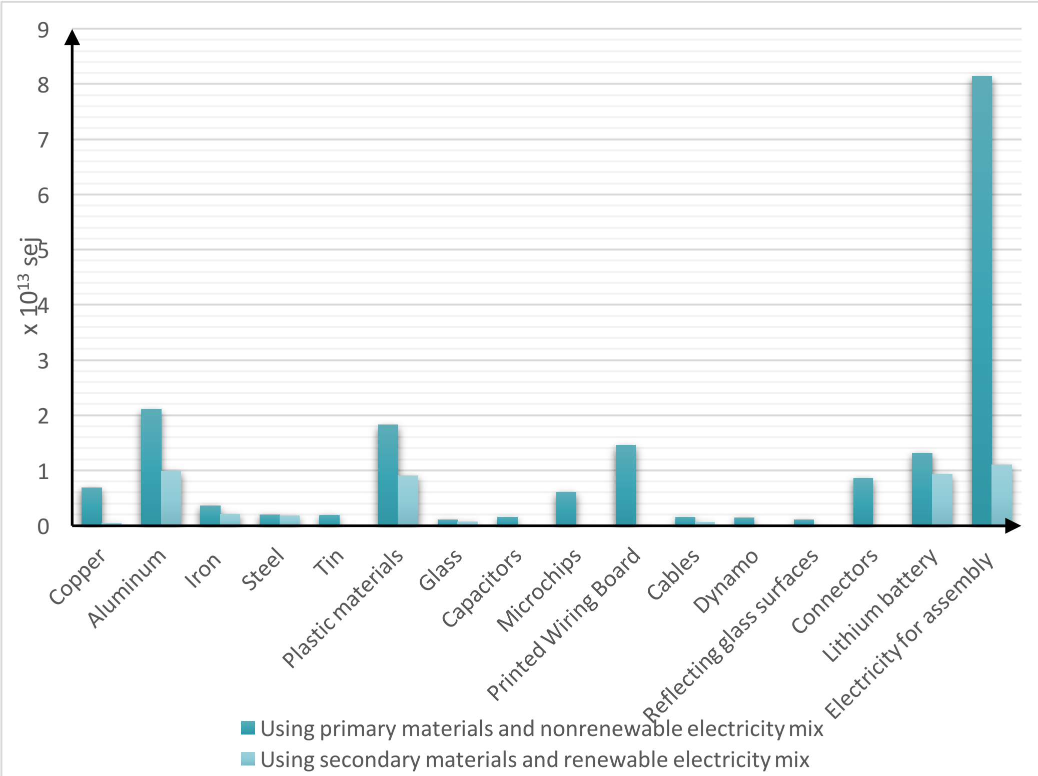



**Figure 3.** Main emergy inflows (x $10^{13}$ sej) to the production of a laptop computer under BAU and RAR assumptions. Only emergy flows higher than 1.0E12 sej are included (form Table 4). Use phase is not included.

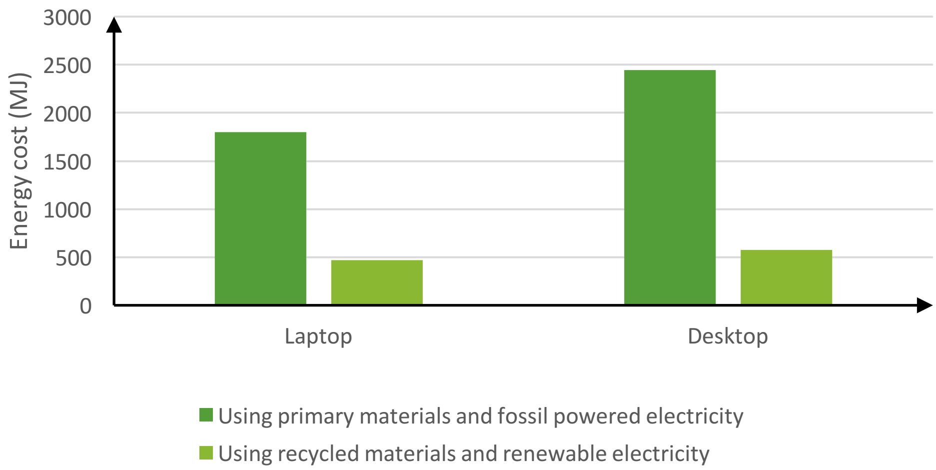



**Figure 4.** Comparison of fossil energy costs of desktop and laptop PC production (BAU and RAR assumptions)

However, the comparison of products with different characteristics (such as the two computers investigated in this study) cannot be made on the basis of extensive indicators, without a clear reference to some of the services provided by the process. A computer may have higher energy production costs compared to another, but its performance in terms of energy use during the operation phase or in terms of computing ability might be much higher. Differences may also be due to the specific technology used for each computer: computers from the 1990's, for example, apart from their lower processing capacity, were bulkier and heavier (higher mass) than current models; desktop PCs are certainly heavier than laptop PCs, in terms of mass; finally, non-negligible differences may also affect computers made by different producers. The current technological advancements due to materials and design innovation may translate into resource savings during both production and use steps (Di Salvo and Agostinho, 2013).

What is needed is therefore a comparison of intensive indicators, i.e. costs and emissions related to one unit of product or of service performed. The cumulative energy, the total emissions and the total emergy associated to the production phase or the use phase or both, can be divided by the mass of a computer, its computing power, or its duration over time, to yield intensive indicators that provide a much more telling figure to which comparison can be drawn. While mass and operative time are well known parameters, the computing ability of a computer may require further explanation to non specialists.

A standard measure of computing power was introduced by informatic specialists, the so-called FLOPS (Floating Point Operations Per Second) (Thakur *et al*, 2013). "Floating Point" refers to a computing modality, which is not of interest in this study. The whole unit FLOPS and its multiple GFLOPS simply indicate how powerful is the computer in performing standardized computing operations. This performance depends on the frequency of the processor and other technical parameters, that change with the model, the age and the design of the processor. The desktop PC investigated in this study has an AMD Athlon(TM) II X2 245 Processor, whose total computing power is estimated around 2.34E+09 GFLOPS (AstroInformatics Group, 2016), whereas the laptop computer uses a Intel(R)Core(TM)2 Duo CPU T7250-2.00GHz processor, characterized by a computing performance of 1.91 GFLOPS/core (AstroInformatics Group, 2016). Core is the processing unit that receives instructions and performs calculations. With 2 cores per processor, we have a processing power of 3.82 GFLOPS for the laptop PC and 4.86 GFLOPS for the desktop PC. Note that these values refer to the processor, so that some uncertainty may be introduced by the computer architecture, capable to affect the computing capacity. Table 5 shows the cumulative energy expenditure, the $CO_2$ emissions and the total emergy investment referred to the computer production phase, the use phase, as well as to one kg of mass, one FLOPS of computing power and finally one hour of operation, for both the laptop and desktop PCs, under the BAU and RAR assumptions.

Table 5 is a huge source of information about the investigated computers. Limiting our attention to the embodied energy category, we can identify a number of interesting results. First of all, in the BAU scenario of desktop PC production the use phase uses 1.8 times more primary energy (MJ of oil equivalent) than the production phase, while for the laptop PC the use phase energy is 48% of the energy for production. This is because of the much larger energy intensity of laptop PC production compared to the desktop PC (610 versus 181 $MJ/kg_{computer}$ respectively, i.e. a ratio of 3.4:1). When we look at the RAR option, a smaller fossil energy difference between production and use phases is detected, with use phase around 87% and 80% of production phase respectively.

**Table 5.** Performance parameters of production and use processes, for both laptop and desktop PCs over BAU and RAR assumptions

| Investigated computer | **Embodied Energy (MJ)** | | | | | | **$CO_2$ emissions ($kg_{CO2\ eq}$)** | | | | | | **Emergy (sej)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total Embodied Energy | E.E. per phase | | Unit E.E. | | | Total $CO_2$ emissions | $CO_2$ per phase | | Unit $CO_2$ release | | | Total emergy | Emergy per phase | | UEV | | Data Power |
| | | Production | Use | $MJ/kg_{computer}$ | $MJ/hr_{use}$ | MJ/FLOPS | | Production | Use | $kg_{CO2eq}/kg_{computer}$ | $kg_{CO2eq}/hr_{use}$ | $kg_{CO2eq}$/FLOPS | | Production | Use | sej/kg | $sej/hr_{use}$ | sej/FLOPS |
| *BAU Desktop PC** | 6770.5 | 2442.6 | 4327.8 | 180.9 | 0.74 | 5.03E-07 | 515.8 | 186.1 | 329.7 | 13.8 | 0.06 | 3.83E-08 | 1.40E+15 | 4.46E+14 | 9.56E+14 | 3.30E+13 | 1.54E+11 | 9.18E+04 |
| *RAR Desktop PC* | 720.9 | 574.9 | 145.9 | 42.6 | 0.08 | 1.18E-07 | 54.9 | 43.8 | 11.1 | 3.2 | 0.01 | 9.01E-09 | 2.72E+14 | 1.41E+14 | 1.30E+14 | 1.04E+13 | 2.97E+10 | 2.90E+04 |
| *BAU Laptop PC** | 3735.1 | 1798.2 | 1936.8 | 609.6 | 0.41 | 4.71E-07 | 284.6 | 137.0 | 147.5 | 46.4 | 0.03 | 3.59E-08 | 6.17E+14 | 1.89E+14 | 4.28E+14 | 6.41E+13 | 6.76E+10 | 4.95E+04 |
| *RAR Laptop PC* | 533.7 | 468.2 | 65.5 | 158.7 | 0.06 | 1.23E-07 | 40.7 | 35.7 | 5.0 | 12.1 | 0.004 | 9.34E-09 | 1.05E+14 | 4.65E+13 | 5.83E+13 | 1.58E+13 | 1.15E+10 | 1.22E+04 |

The weight of the desktop PC is 13.5 Kg; the weight of the laptop PC is 2,95 Kg; assumed 9125 $hr_s$ of operation over 5 years. Definition of FLOPS is provided in the text. Computing power of desktop PC is 4.86E+09 FLOPS, while it is 3.82E+09 FLOPS for the laptop PC. When calculating intensity indicators per $kg_{computer}$, and per unit of computing power, only the energy, $CO_2$ emissions and emergy related to the production phase are included; instead, when referring to one hour of operation, both production and use phase costs and emissions must be accounted for.

The fossil energy cost of a laptop PC production is 159 $MJ/kg_{computer}$ while it is only 43 $MJ/kg_{computer}$ in the case of a desktop PC, i.e. a ratio of 3.7:1. Results show that a laptop PC consumes less energy in the use phase, but its production is more energy intensive. If focus is placed on computing capability, much more telling than computer's mass, the laptop PC shows a slightly better performance (4.71E-7 MJ/FLOPS) than the desktop PC (5.03E-7 MJ/FLOPS) in the BAU scenario, while the RAR scenarios are fully equivalent for both computers. Finally, if operation energy costs are added to production costs and properly allocated to one hour of working activity over 5 years, the desktop PC requires 0.7 MJ/hr compared to only 0.4 MJ/hr of the laptop PC in the BAU scenario. Instead, in the RAR assumption, the energy costs are 0.08 and 0.06 MJ/hr respectively for the desktop and the laptop PC. It clearly appears that when focus is placed on production, the laptop process is much more energy intensive, while the opposite is true in the use phase. The improvements in the RAR scenario are affected accordingly.

Still looking at Table 5, it clearly appears that $CO_2$ emissions follow a trend that parallels the cumulative energy use. While BAU and RAR represent the two extremes of highest and lowest possible emissions of $CO_2$, real cases fall within the ranges indicated in Table 5 and depend on the extent of recycling and renewable energy efforts. The added value of a deep look at $CO_2$ emissions relies on the specific importance of these emissions to climate change. While energy consumption may not appear the most urgent problem to survival, considering the still existing fossil energy storages (mainly coal) and replacement options, the consequences on global warming are instead well identified and their urgency clearly pointed out (IPCC, 2007; Rockström *et al*, 2009; COP21, 2015). The possibility to decrease $CO_2$ emissions relies on a number of choices. First of all, implementing to the largest possible extent the recycle of materials and the use of renewable energy sources in the production phase (RAR scenario). Table 5 clearly shows that this strategy is capable to achieve huge decreases of $CO_2$ emissions. Secondly, obsolescence of electronic devices should be prevented to the largest possible extent (not to talk of "planned" obsolescence). Most often, the available memory space is occupied by software and updates that are of no interest for the user's activity but make the computer slow or prevent further use of some of its functions. Extending the useful lifetime of computers by means of accurate maintenance, and prevention of useless software installation and updates would proportionally decrease the $CO_2$ emissions in both production (indirectly) and use phases (directly). Tables 3 and A1 as well as Figure 3 also show which are the most energy demanding inflows to the production phase and where the largest savings can be achieved (aluminium, plastic materials, printed wiring board, lithium battery, connectors and electricity for assembly): redirecting efforts and investments in better technologies and more recycling of these components would ensure the largest return in terms of environmental protection. Finally, much better performances per hour and per FLOPS are provided by the laptop technology (Table 5), which therefore candidates to be a more environmental friendly tool for personal computing, at least for those uses that do not require very high computing capability (e.g. as servers). Results in Table 5 confirm a previous study performed by the European Commission (2007), where material extraction, production, manufacturing and distribution of a laptop computer account for about 1634 MJ (1798 MJ in our study) of energy use and release approximately 90.51 kg of $CO_2$ equiv (137 kg in our study).

The added value of also calculating emergy performance indicators (Table 5) relies on the fact that emergy also captures the process of resource generation (i.e. their actual replacement time) and the environmental support to generating minerals, water, and ecosystem services, all important components of any economic process and computer production in particular, in addition to energy supply. In the emergy accounting procedure (Table 4), the most significant emergy inflows to a laptop production are aluminium, plastic materials, PWB, connectors and lithium battery and, of course, electricity for assembly (Figure 3), whereas for a desktop PC the main input flows are iron, copper, aluminium, tin, connectors, monitor and electricity (Table A2, Appendix). Accounting for the environmental cost of materials (Tables 4 and A2) confirms the situation previously computed about energy costs (Table 3 and A1) and provides a deeper insight into additional savings achievable on the material side. In fact, $emergy_{BAU}/emergy_{RAR}$ ratios of production phase are higher for the desktop computer than for the laptop, due to the larger demand for materials in the former device. The same ratios remain stable in the use phase, so that changes in the performance indicators (emergy per unit mass, emergy per unit time and emergy per computing power) only depend on construction phase and specific technical characteristics. In all cases, the $emergy_{BAU}/emergy_{RAR}$ are lower for the laptop computer performance indicators: this means that, being the laptop computer less emergy demanding in its production phase, it is already optimized under environmental cost-performance aspects.

Our results confirm previous studies on computer production and use (Williams, 2004; Choi *et al*., 2006) that highlight the higher energy consumption and carbon footprint impact being associated to the manufacturing of the device. However, the use phase may increase its importance depending on the characteristics of the electricity supply and its percentage of renewability (Arushanyan and Moberg, 2012). Our emergy results are also in good agreement with Di Salvo and Agostinho (2013). These Authors, investigating the emergy costs and the computing capacity of ten different laptops in the market, suggested an average unit emergy value of computing power around 1.7E+4 sej/FLOPS (without services), whereas in our case the unit emergy value for the laptop is 4.95E+4 sej/FLOPS. The higher production and use emergy costs for the desktop PC translate into a much higher value around 9.18E+4 sej/FLOPS.

The actual feasibility of our RAR scenario is confirmed by studies performed by Kanth *et al.* (2010) as well as Hadi *et al.* (2015) about the non-negligible energy cost reduction that can be achieved in the electronics manufacturing industry by reducing the energy demand of the manufacturing process as well as materials used to produce the PCB (Printed Circuit Board, or Printed Wiring Board, PWB). Bogdanski *et al.* (2012) underlined the possibility of large savings in energy consumption for PCB.

Even if recycling shows large improvement potential, reuse of materials would be even more beneficial. Recycling has, anyway, a cost for the process to occur, while reuse saves at the same time materials and process energy. However, the computer manufacturing industry seems to prefer the use of recycled materials, due to market and technological reasons linked to the need to meet the power demand required by the latest software generation (Rubin *et al*., 2014).

*Conclusions*

The energy, $CO_2$ and emergy flows associated to the production and use of personal computers are assessed in this study, under BAU (Business as Usual) and a RAR (Recycling and Renewable) scenarios. Results show to what extent the use of renewable energies and recycled materials largely contribute to the decrease of energy costs and environmental impacts. Results also identify which materials are the most important inflows to be optimized or replaced for energy and environmental improvements. Considering the large environmental impact of the computer industry in terms of resource use as well as the need for appropriate disposal of waste electric and electronic equipments (WEEE), the advantages identified in this study for the Recycling and Renewable scenario suggest an important strategy to address the consequences of the day-by-day increasing number of electronic devices worldwide.

**Appendix.**

**Table A1**. Embodied Energy Analysis of the production and operation of a desktop PC

| **Desktop PC** | | **Using primary materials and nonrenewable electricity mix** | | **Using secondary materials and renewable electricity mix** | |
|---|---|---|---|---|---|
| **Inventory** | **Amount (g)*** | **Energy intensity (MJ/g)*** | **Embodied Energy (MJ)** | **Energy intensity (MJ/g)*** | **Embodied Energy (MJ)** |
| **Materials** | | | | | |
| Copper | 186.00 | 0.06 | 10.96 | 0.02 | 2.98 |
| Aluminum | 825.00 | 0.16 | 132.65 | 0.03 | 23.93 |
| Iron | 7360.00 | 0.05 | 351.77 | 0.01 | 36.80 |
| Steel | 104.00 | 0.10 | 10.52 | 0.01 | 0.94 |
| Tin | 12.00 | 0.34 | 4.14 | 0.05 | 0.58 |
| Brass | 5.00 | 0.07 | 0.34 | 0.04 | 0.10 |
| Plastic materials | 2988.09 | 0.10 | 298.81 | 0.03 | 95.62 |
| Glass | 813.00 | 0.02 | 16.26 | 0.01 | 8.94 |
| **Microcomponents** | | | | | |
| Internal clock nickel battery | 3.00 | 0.26 | 0.78 | 0.08 | 0.24 |
| Led | 0.37 | 16.81 | 6.15 | 15.77 | 5.77 |
| Capacitors | 79.31 | 0.44 | 34.55 | 0.20 | 15.95 |
| Inductors | 69.49 | 0.12 | 8.49 | 0.11 | 7.94 |
| Microchips | 16.83 | 6.20 | 104.31 | 2.98 | 50.09 |
| Printed Wiring Board | 322.40 | 2.78 | 896.27 | 0.86 | 278.45 |
| Cables | 399.00 | 0.11 | 41.95 | 0.04 | 14.81 |
| Diodes | 1.77 | 9.45 | 16.71 | 1.93 | 3.42 |
| Resistances | 7.30 | 0.44 | 3.21 | 0.03 | 0.25 |
| Reflecting glass surfaces | 33.00 | 0.02 | 0.66 | 0.01 | 0.36 |
| Polarizers | 41.00 | 0.02 | 0.82 | 0.01 | 0.41 |
| Transistors | 35.10 | 0.35 | 12.45 | 0.04 | 1.40 |
| Connectors | 140.54 | 0.06 | 9.11 | 0.06 | 8.00 |
| Magnets | 60.10 | 0.03 | 1.80 | 0.03 | 1.80 |
| **Assembly** | | | | | |
| Electricity for assembly (kWh)* | 56 | 8.57 | 479.92 | 0.29 | 16.24 |
| **Final product** | | | | | |
| Mass of assembled computer | 13502.29 | | | | |
| Cumulative energy demand | | | 2442.65 | | 574.95 |
| Oil equivalent (kg)* | | | 58.16 | | 13.69 |
| **Five year operation** | | | | | |
| Electricity for 5 year operation (kWh)* | 505.00 | 8.57 | 4327.85 | 0.29 | 145.95 |
| Oil equivalent (kg)* | | | 103.04 | | 3.47 |
| **CO2 emissions** | | | | | |
| | | **Conversion factor ($kgCO2_{eq}/kgoil_{eq}$)** | **CO2 release ($kgCO2_{eq}$)** | **Conversion factor ($kgCO2_{eq}/kgoil_{eq}$)** | **CO2 release ($kgCO2_{eq}$)** |
| **Total CO2 eq emission** | | 3.2 | 515.85 | 3.2 | 54.9 |

* Unit of electricity input flow is kWh; unit of energy intensity of electricity is MJ/kWh; unit of oil equivalent is kg.

**Table A2.** Emergy analysis of the production and operation of a desktop PC

| Desktop PC | | Using primary materials and nonrenewable electricity mix | | Using secondary materials and renewable electricity mix | |
|---|---|---|---|---|---|
| **Inventory** | **Raw Amount (g)*** | **UEV (sej/g)*** | **Emergy (sej)** | **UEV (sej/g)*** | **Emergy (sej)** |
| **Materials** | | | | | |
| Copper | 1.86E+02 | 1.07E+11 | 1.99E+13 | 8.88E+09 | 1.65E+12 |
| Aluminum | 8.25E+02 | 5.09E+10 | 4.20E+13 | 2.39E+10 | 1.97E+13 |
| Iron | 7.36E+03 | 1.28E+10 | 9.42E+13 | 7.40E+09 | 5.45E+13 |
| Steel | 1.04E+02 | 2.07E+10 | 2.15E+12 | 1.91E+10 | 1.99E+12 |
| Tin | 1.20E+01 | 1.75E+12 | 2.10E+13 | 5.00E+10 | 6.00E+11 |
| Brass | 5.00E+00 | 1.20E+10 | 6.00E+10 | 1.04E+10 | 5.20E+10 |
| Plastic materials | 2.99E+03 | 2.97E+10 | 8.87E+13 | 1.48E+10 | 4.42E+13 |
| Glass | 8.13E+02 | 4.56E+09 | 3.71E+12 | 2.96E+09 | 2.41E+12 |
| **Microcomponents** | | | | | |
| Internal clock nickel battery | 3.00E+00 | 2.38E+11 | 7.15E+11 | 3.85E+10 | 1.15E+11 |
| Led | 3.66E-01 | 2.19E+10 | 8.02E+09 | 1.31E+08 | 4.79E+07 |
| Capacitors | 7.93E+01 | 5.32E+10 | 4.22E+12 | 4.03E+07 | 3.19E+09 |
| Inductors | 6.95E+01 | 9.03E+09 | 6.27E+11 | 5.51E+08 | 3.83E+10 |
| Microchips | 1.68E+01 | 2.39E+11 | 4.02E+12 | 6.60E+08 | 1.11E+10 |
| Printed Wiring Board | 3.22E+02 | 4.90E+10 | 1.58E+13 | 5.65E+08 | 1.82E+11 |
| Cables | 3.99E+02 | 7.49E+09 | 2.99E+12 | 3.25E+09 | 1.30E+12 |
| Diodes | 1.77E+00 | 4.74E+10 | 8.38E+10 | 8.91E+08 | 1.58E+09 |
| Resistances | 7.30E+00 | 1.13E+08 | 8.25E+08 | 4.85E+06 | 3.54E+07 |
| Reflecting glass surfaces | 3.30E+01 | 2.67E+10 | 8.82E+11 | 1.65E+07 | 5.45E+08 |
| Polarizers | 4.10E+01 | 2.67E+10 | 1.10E+12 | 1.99E+08 | 8.16E+09 |
| Transistors | 3.51E+01 | 2.25E+10 | 7.90E+11 | 3.22E+08 | 1.13E+10 |
| Connectors | 1.41E+02 | 2.57E+11 | 3.61E+13 | 1.61E+08 | 2.26E+10 |
| Magnets | 6.01E+01 | 9.10E+09 | 5.47E+11 | 2.56E+06 | 1.54E+08 |
| **Assembly** | | | | | |
| Electricity for assembly (kWh)* | 56 | 1.89E+12 | 1.06E+14 | 2.58E+11 | 1.44E+13 |
| **Final product** | | | | | |
| Mass of assembled computer (g) | 2.95E+03 | | | | |
| Total emergy of production (sej) | | | 4.46E+14 | | 1.41E+14 |
| **Five year operation** | | | | | |
| Electricity for 5 year operation (kWh)* | 505 | 1.89E+12 | 9.56E+14 | 2.58E+11 | 1.30E+14 |
| Total emergy of production and operation (sej) | | | 1.40E+15 | | 2.71E+14 |

* Unit of electricity input flow is kWh; therefore unit of UEV of electricity is sej/kWh

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# CHAPTER 7.b Life Cycle Assessment of a recycling process for crystalline silicon photovoltaic panels end-of-life

*Introduction*

Many laboratory-scale or pilot industrial processes have been and are being developed recently by private companies and public research institutes worldwide to demonstrate the real potential offered by the recycling of PV panels. The value of recycling lies in environmental benefits, market acceptability and support, environmental regulations, and resources availability. In particular, the environmental benefits of recycling products are, in general, related to savings in landfill space, energy, emissions and raw materials. Especially for strategic materials like precious metals and rare earths (such as Lanthanides), these benefits are crucial as the extraction processes of raw materials are often associated with high energy and auxiliary demands and related emissions (U.S. EPA, 2006). However, waste from society's consumption of industrial products must be treated using energy intensive processes in order to prevent environmental and public health liabilities. The treatment of these waste, or rather transformation into materials still usable by humans or nature, remains crucial in the face of energy and resources scarcity worldwide, also including the environment as a sink of output flows. An assessment of the environmental costs and benefits of PV panel material recycling requires a comprehensive investigation on the impacts due to the recycling processes of materials as well as on the avoided impacts gained by returning materials to the production chain. Life Cycle Assessment (LCA) has been demonstrated to be an appropriate tool for this aim and its application in this field has rapidly expanded over the last few years (EC, 2010).

As a follow up of a wider project, entitled F.E.R.G.E. ("Devices, Techniques and Enabling Technologies for Renewable Energy Sources Toward Green Economy"), funded by the Italian Ministry of Education, University and Research [MIUR] in 2013, as well as within the framework of the EU project EUFORIE, this work presents the results of a Life Cycle Assessment of a thermal recovery process for EoL c-Si PV panels (for further details, see Corcelli et al., 2016). The overall goal of this study is to compare different EoL scenarios, focusing on the evaluation of the environmental, material and energy advantages of replacing virgin materials with recovered resources.

*Materials and methods*

In this study, the methodology and concepts developed for LCA – defined by ISO standards and ILCD Handbook guidelines (EC, 2010, 2011; ISO, 2006 a, b) – are used for the evaluation of an innovative recovery process of c-Si PV panels. LCA models of waste management generally calculate environmental burdens per unit amount of waste treated without considering how the latter was generated. Hence in the evaluation of waste management, instead of the traditional approach ‘from cradle to grave’, the starting point of the analysis will be the point where the waste is generated. This approach is called ‘zero-burden’ and suggests that waste entry into the system is considered as free from the impacts of the process that has contributed to its production (Ekvall et al., 2007). Thus, a ‘zero-burden waste’ approach is adopted in this study, not including the upstream generation of waste (i.e. only the processing inputs – recovery and recycling – are accounted for, disregarding the upstream production chain of the PV modules the cost of which is not attributed to the final waste material) (Bala Gala et al., 2015).

*Goal and scope*

The goal of this LCA was to assess the potential environmental impacts related to a PV panel recycling process and to identify its environmental hotspot (i.e. processing stages with the most relevant impacts). The functional unit of the LCA was the 1 $m^2$ of EoL c-Si PV panel treated.

A photovoltaic panel is made in layers. The crystalline silicon cell is wrapped with EVA (ethylene-vinyl-acetate) and then with tempered glass on the upper surface, and PVF (polyvinyl-fluoride) or glass as back sheet. The EVA layer is used like an adhesive between the tempered glass and PV cell. In Table 1 the typical composition of a crystalline silicon (c-Si) panel is reported.

The recovery and recycling of a PV panel requires the panel disassembling in its components. Generally, the process flow begins with the disassembly of the aluminum frame and junction box, frequently done manually, followed by removal of the EVA layer, in order to separate the glass from the silicon cell (Kang et al., 2012). The most common method used to decompose the EVA layer is the thermal treatment (Allen et al., 2000). The present study is based on a technical feasibility laboratory test performed within the Italian National Agency for New Technologies, Energy and the Environment (ENEA) laboratories in Portici (Napoli). The experimental test was performed on a representative sample of a crystalline silicon panel, whose characteristics are shown in Table 2.

***Table 1.*** *Typical composition of a crystalline silicon panel (Source: Sander et al., 2007)*

| Component | Weight percentage (%) |
|---|---|
| Aluminium (frame) | 10.30 |
| Glass | 74.16 |
| Silica cell | 3.48 |
| EVA | 6.55 |
| PVF (back sheet film) | 3.60 |
| Electrical contacts | 0.75 |
| Adhesives, etc. | 1.16 |

**Table 2.** Technical features of c-Si panel used in the experimental test.

| Photovoltaic panel – main characteristics | |
|---|---|
| Origin | Italian |
| Technology | PolySi |
| Fabrication year | 1986 |
| Dimensions (cm) | 130 x 68 |
| Total weight (kg) | 12.694 |
| Frame weight (kg) | 3.294 |
| Layers type (thickness) | glass-cell-PVF (43mm) |
| Cell: shape; size; thickness | Square; l =10cm; 0.48 mm |
| Total numbers of cells | 72 |

The sample under study, 10x10 cm in size, was obtained as follow: after removing the aluminum frame and the junction box, the sample was cut with a circular saw, placed inside a furnace and under a stream of air, then heated from ambient temperature until 600°C, keeping it at this temperature for 30 minutes (Tammaro et al., 2015). The final temperature and the duration of the test have been chosen to ensure that the thermally degradable parts of the panel were substantially eliminated (i.e. PVF and EVA decompose around 450 °C and 350 °C, respectively).
The thermal treatment outputs were a recoverable fraction of valuable materials (glass, metals, silicon, electrodes), which may be sorted for recycling, as appropriate, and a fraction of smaller particles which is referred to as ashes in Table 3.

**Table 3.** Amount of recovered material from c-Si PV panel, referred to a functional unit of 1 $m^2$.

| Process | Recovered materials | ($kg/m^2$) |
|---|---|---|
| Thermal treatment | Aluminum (frame) | 3.72 |
| | Glass | 8.14 |
| | Silicon | 0.98 |
| | Metal electrodes[a] | 0.07 |
| | Ashes (metals, inert) | 0.05 |

Source: Tammaro et al. (2015) – modified.

[a] 50% of metal electrodes is assumed to be made of copper (Jungbluth et al., 2012).

The boundary of the analyzed system includes two subsystems: the thermal treatment of the decommissioned PV panel and the subsequent recycling of the recoverable fractions. In particular, after the thermal treatment of the c-Si PV panel, two different scenarios can be designed:

• a high-rate (HR) recovery scenario (Fig. 1a), where the heat produced by the plastics thermal treatment is recovered and then exploited for hot water generation or for heating purpose within the plant where the process takes place. Several materials are recovered during the process: except for the aluminum – whose disassembling is done before the thermal treatment – glass, silicon and copper are recovered through manual separation after the thermal treatment; Fe and non-Fe metals are mechanically sorted from ashes thermal treatment. After the recovery, these materials are sent to recycling process to obtain secondary raw materials whilst the inert fraction of the ashes is assumed to be used for the clinker production in cement plants, in accordance with the Italian and international literature (Grosso et al., 2010);

• a low-rate (LR) recovery scenario (Fig. 1b): only the aluminum frame and glass are recycled and the not-recovered (here in after referred as residual) fraction of copper, silicon and ashes is disposed of in a sanitary landfill.

*Life Cycle Inventory (LCI)*

In this study the environmental impacts are analyzed with reference to 1 $m^2$ of PV panel treated (functional unit). During the inventory phase, local data were collected for each of the above mentioned scenarios: all different materials, machinery, as well as the energy consumption for all the steps. At industrial scale the thermal treatment would require machineries and facilities to run the process (e.g. scrubber or the heat exchanger for the exhaust gases treatment); to this purpose, a scale-up scenario was designed in order to include the capital goods impacts in the analysis. Data were obtained from multiple sources. Foreground data, e.g. specific information about recovered materials and heavy metals emissions related to the experimental thermal treatment, were provided by ENEA in the framework of F.E.R.G.E Project. Transportation of recovered materials was considered negligible as the sites for the collection of the PV panels, treatment and disposal were assumed to be in the same area. When direct measurements were not available, estimations were made by experts and their consistency was verified in literature.

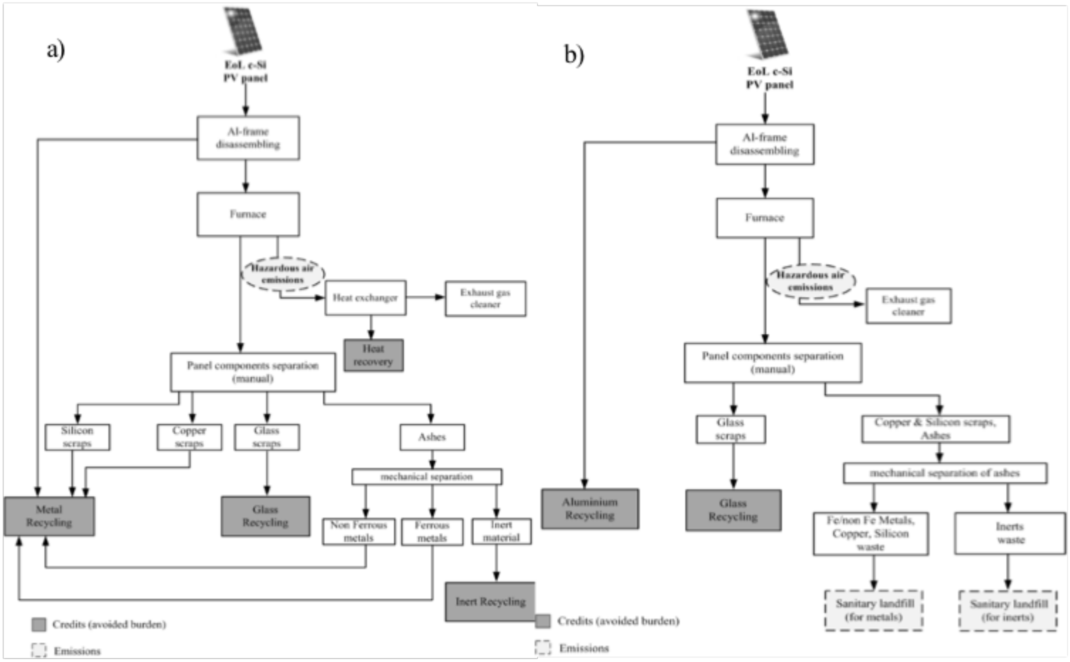



**Figure 1.** (a) Flow chart of high-rate recovery scenario (HR). (b) Flow chart of low-rate recovery scenario (LR).

Background data over the supply chain of energy and materials were derived from the Ecoinvent v3.1 database, as well as all the data regarding waste treatments included in the proposed scenarios such as treatment of waste in sanitary landfill or in incineration plant, also including wastewater treatment, ash disposal, airborne and waterborne emissions. Capital goods and related environmental impacts were also included in the analysis, as well as the recycling costs related to materials recovery. The average European production mix of medium voltage electricity (Ecoinvent v.3.1, 2014) was used for crediting energy supply, whilst for crediting resources recovery, the avoided virgin production of equivalent materials was assumed.

*Life Cycle Impact Assessment (LCIA)*

The environmental assessment of the process was accomplished by means of LCA Professional software SimaPro 8.0.4.30, integrated with Ecoinvent v3.1 database. In particular, the impact assessment was performed by means of one of the most recent and up-to-date LCA methods, the ReCiPe method (Goedkoop et al., 2009). It provides characterization factors to quantify the contribution of processes to each impact category and normalization factors to allow a comparison across categories. In this study, the following impact categories are considered: Global Warming Potential (GWP, in kg $CO_2$eq), Photochemical Oxidant Formation Potential (POFP, in kg NMVOC), Terrestrial Acidification Potential (TAP, in kg $SO_2$eq), Freshwater Eutrophication Potential (FEP, in kg P eq), Terrestrial Ecotoxicity Potential (TEP, kg 1,4-DB eq), Human Toxicity Potential (HTP, in kg 1,4-DB eq), Water Depletion

Potential (WDP, in m3), Metal Depletion Potential (MDP, in kg Fe eq), Fossil Depletion Potential (FDP, in kg oil eq).

*Results*

The performed analysis has two objectives: (1) to identify the flow(s) or steps that are most "responsible" of the environmental impacts in the PV panel thermal treatment and resources' recovery; (2) to ascertain the environmental benefits of two different recovery scenarios, having in common the thermal treatment of the EoL panel and differing by the recovery rate. The avoided costs, deriving from the possible recovery of materials were in both cases considered. In the present study, environmental costs of goods and energy were subtracted from the accounting of the system's impacts, considering that their production by conventional routes is avoided. When calculated impacts show negative values, they indicate that savings in the production of virgin metals and heat by conventional routes are allowed and environmental benefits are attained.

Fig. 2 presents the normalized impacts of the thermal treatment phase (numbers are unit-less values that express a comparison with the chosen reference normalization standards). The most affected indicators are freshwater eutrophication (6.3E−03), human toxicity (4.2E−03) and fossil depletion (3.2E−03) and the major impact to all categories comes from the Italian medium voltage electricity mix (breakdown not shown in the figure, due to overwhelming percentage of electricity, around 98–99%), being electricity the only source of energy for thermal treatment. About 50% of this contribution is associated to the import of natural gas from foreign countries (24% from Russia, 16% from Algeria, 5% from the Netherlands, 5% from other countries).

Table 4 summarizes, for each single recovery process (which includes the thermal treatment phase), the characterized results related to the HR and LR scenarios. In the HR scenario, the environmental benefits – i.e. negative values – from recovery are much higher than the environmental loads in all impact categories, with minor impacts still associated to heat, copper, inert and steel recovery. In the global warming category, the most relevant benefits are achieved thanks to silicon and aluminum recovery, amounting to −63.40 and −20.60 kg $CO_2$eq/$m^2$panel, respectively, whilst a smaller benefit is provided by glass recovery (−3.65 kg $CO_2$eq/$m^2$panel). Silicon recovery and aluminum recovery also contribute to the largest avoided impacts in the human toxicity category, with −23.40 1,4-DB eq/$m^2$panel and −16.60 1,4 DB eq/$m^2$panel, respectively. Regarding the fossil depletion category, the most pronounced environmental benefits are provided by silicon recovery, corresponding to avoided impacts of −16.60 kg oil eq/$m^2$panel.

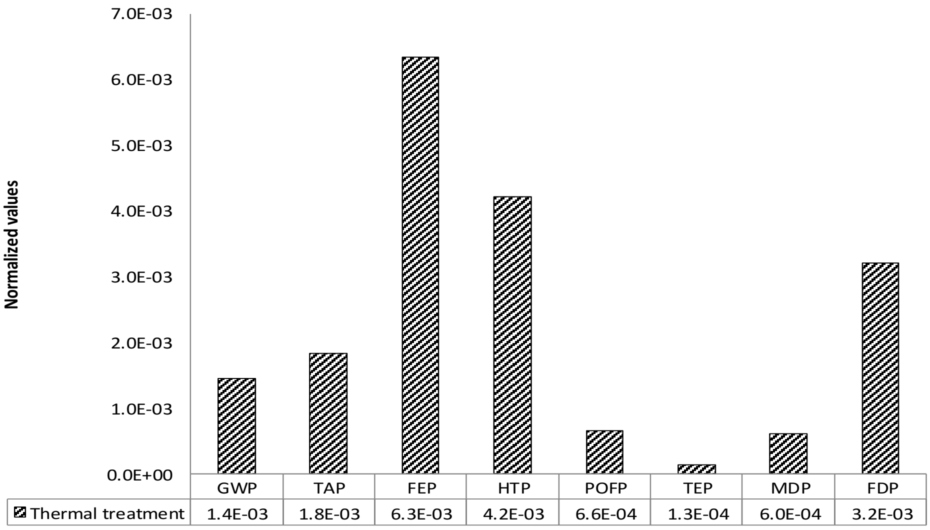



**Figure 1.** Normalized impacts of the thermal treatment.

In the LR scenario, the GWP environmental advantage of the aluminum recovery (−18.50 kg $CO_2$eq/m$^2$panel) is greater than the recovery of glass (−3.49 kg $CO_2$eq/m$^2$panel). Instead, a non-negligible GWP impact, around 2.79 kg $CO_2$eq/m$^2$panel, is generated by the landfill disposal of the residual fraction (including silicon, copper and ashes of the thermal treatment). In the human toxicity category, the aluminum recovery provides relevant benefits (−16.20 1,4 DB eq/m$^2$panel), with the glass recovery playing a minor role (−1.61 1,4 DB eq/m$^2$panel) as well. In the remaining impact categories, contributions from the two scenarios do not differ markedly.

Fig. 3 shows the contributions of each single phase of HR and LR scenarios to the normalized impacts in all the investigated impact categories. In the case of HR, the environmental benefits overcome the environmental loads in all impact categories, but some burdens are provided by the recovery of heat, especially in POFP and MDP indicators, corresponding to impacts of 1% and 2%, respectively. Nevertheless, a net advantage (with the negative part much larger than the positive one) is reached in all the impact categories. In particular, environmental advantages from the silicon recovery are achieved in all the analyzed categories, ranging from a minimum of 56% in human toxicity to a maximum of 80% in freshwater eutrophication. Beyond silicon recovery, the second main contribution to environmental benefits comes from the recovery of aluminum in all impact categories, except for terrestrial ecotoxicity and metal depletion. It is worth to point out that silicon and aluminum recovery are the main responsible of the negative values, equaling together more than 70% of the total avoided impact in all categories. In particular, FEP and GWP are the indicators where the avoided (i.e. negative) burden given by silicon and aluminum reaches 99% and 96%, respectively. Overall, a positive performance also in the LR scenario, thanks to the recovery of glass and aluminum is noticeable. In particular, the environmental benefits of the aluminum recovery are achieved in all analyzed categories, with values ranging from a minimum of 78% in terrestrial ecotoxicity to a maximum of 92% in fresh-water eutrophication. However, unlike the HR, the impacts (i.e. positive values) of the process are more evident due to disposal of the residual fraction. Especially in the metal depletion and fossil depletion categories, the disposal phase contributes to the impact with a share of 20% approximately.

**Table 4** Characterized impacts calculated for the high-rate and low-rate scenarios (broken down into different process steps), referred to a functional unit of 1 m2 c-Si PV panel treated. Negative values correspond to avoided impacts thanks to recovery.

| **Categ indic.** | **Unit/m² PV panel treated** | **Aluminium recovery** | | **Copper recovery** | **Glass recovery** | | **Inert recovery** | **Silicon recovery** | **Steel recovery** | **Heat recovery** | **Landfilling of ashes, copper, silicon** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | HR | LR | HR | HR | LR | HR | HR | HR | HR | LR |
| GWP | kg $CO_2$ eq | -2.06E+01 | -1.85E+01 | 4.63E-01 | -3.65E+00 | -3.49E+00 | -2.00E-05 | -6.34E+01 | -3.01E-05 | 2.66E-01 | 2.79E+00 |
| TAP | kg $SO_2$ eq | -2.03E-01 | -1.95E-01 | 5.62E-04 | -4.59E-02 | -4.53E-02 | 1.49E-06 | -3.34E-01 | -8.75E-08 | 3.48E-03 | 1.10E-02 |
| FEP | kg P eq | -1.33E-02 | -1.9E-02 | -1.97E-04 | -6.35E-04 | -6.09E-04 | -3.65E-09 | -3.01E-02 | -8.19E-09 | 4.02E-04 | 4.59E-04 |
| HTP | kg 1,4-DB eq | -1.66E+01 | -1.62E+01 | -4.88E-01 | -1.64E+00 | -1.61E+00 | -2.66E-05 | -2.34E+01 | 2.34E-05 | 2.64E-01 | 4.76E-01 |
| POFP | kg NMVOC | -9.77E-02 | -9.27E-02 | 5.52E-04 | -2.43E-02 | -2.40E-02 | 1.83E-06 | -1.80E-01 | -1.19E-07 | 3.65E-03 | 6.61E-03 |
| TEP | kg 1,4-DB eq | -8.88E-04 | -7.54E-04 | 2.27E-06 | -1.76E-03 | -1.75E-03 | -5.05E-08 | -5.02E-03 | 6.38E-09 | 4.74E-05 | 1.81E-04 |
| WDP | $m^3$ | -5.10E-01 | -4.97E-01 | -1.00E-03 | -2.35E-02 | -2.26E-02 | -4.51E-08 | -1.63E+00 | -9.15E-07 | 2.74E-02 | 1.42E-02 |
| MDP | kg Fe eq | -2.36E-01 | -1.82E-01 | -5.26E-01 | -1.36E-01 | -1.32E-01 | -1.46E-06 | -1.19E+00 | -2.21E-05 | 4.72E-02 | 7.46E-02 |
| FDP | kg oil eq | -3.28E+00 | -2.65E+00 | 1.42E-01 | -9.01E-01 | -8.51E-01 | -1.24E-05 | -1.66E+01 | -3.75E-06 | -2.36E-02 | 8.61E-01 |

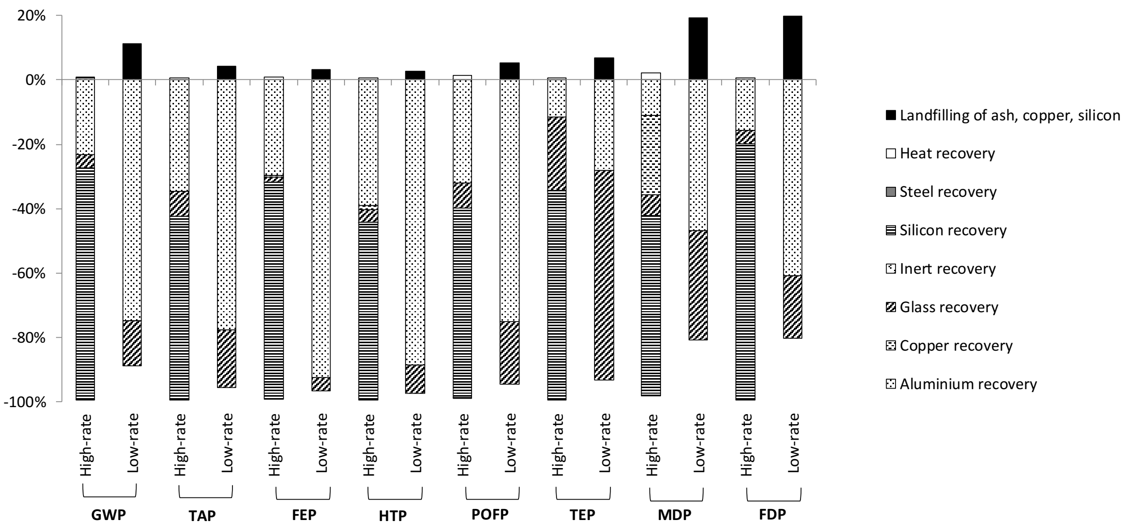



**Figure 2.** Contributions to normalized impacts from each single phase of high-rate and low-rate scenarios.

Table 5 compares the final characterized results achieved by applying the ReCiPe Midpoint (H) method to HR and LR scenarios, with reference to the usual functional unit.

**Table 5.** Characterized impacts calculated for the high-rate and low-rate scenarios, referred to a functional unit of 1 $m^2$ c-Si PV panel treated. Negative values correspond to avoided impacts thanks to recovery.

| Category indicator | Unit/$m^2$ PV panel treated | HR | LR |
|---|---|---|---|
| GWP | kg $CO_2$ eq | -8.69E+01 | -1.92E+01 |
| TAP | kg $SO_2$ eq | -5.79E-01 | -2.29E-01 |
| FEP | kg P eq | -4.39E-02 | -1.31E-02 |
| HTP | kg 1,4-DB eq | -4.18E+01 | -1.73E+01 |
| POFP | kg NMVOC | -2.98E-01 | -1.10E-01 |
| TEP | kg 1,4-DB eq | -7.61E-03 | -2.32E-03 |
| WDP | $m^3$ | -2.14E+00 | -5.06E-01 |
| MDP | kg Fe eq | -2.04E+00 | -2.39E-01 |
| FDP | kg oil eq | -2.06E+01 | -2.64E+00 |

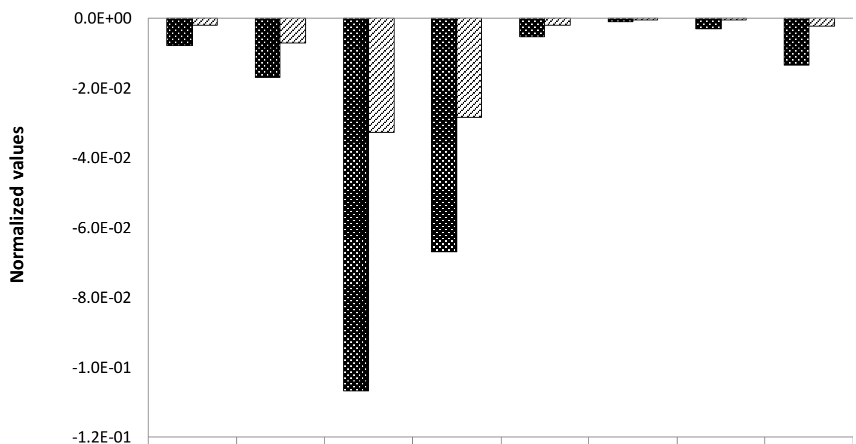
All the resulting values are negative, meaning that both scenarios turn out to be favorable (i.e. contribute to decrease impacts) thanks to the recovery of materials that can be reintegrated in the production chains. In particular, HR scenario shows the highest avoided impacts, in comparison with LR scenario, in all the impact categories, especially GWP, HTP and FDP indicators, corresponding to −8.69E+01 $CO_2$eq/$m^2$panel (four times better than LR scenario), −4.18E+01 kg1,4-DB eq/$m^2$panel (two times better than LR scenario) and−2.06E+01 kg oil eq/$m^2$panel (eight times better than LR scenario), respectively. If normalized values of impacts are taken into account (Fig. 4), according to Europe ReCiPe Midpoint (H) method normalization factors, a comparison across impact categories becomes possible. HR is the best performing scenario in terms of avoided burdens, in all impact categories. The most pronounced environmental benefits are achieved by HR in FEP and HTP indicators, corresponding to −1.1E−01 and −6.7E−02, respectively. WDP indicator is not detectable at all, due to the normalization factor equal to zero, and it is not shown in Fig. 4.

*Discussion*

The results of this study show that the recovery process of the poly-crystalline silicon photovoltaic panels displays non-negligible benefits from both energy and environmental points of view.

In order to have a more detailed analysis of the most impacting steps and processes, the entire process was broken down into two sub-processes: thermal treatment, aimed at energy and material separation and recovery from the panel, and the recycling process, directed to the refining of recovered products to produce secondary raw

materials. According to Table 5, the negative values achieved for the entire process mean that the avoided impacts are greater than the burden caused to the environment, thanks to the recycling process and to the recovery of secondary raw materials able to replace primary inputs. In particular, the comparison between high-rate (HR) and low-rate (LR) scenarios, shows important differences in terms of avoided costs: HR presents the highest avoided impacts in all indicators analyzed – with the larger environmental benefits arising from the recovery of silicon and aluminum (Fig. 4).
In the light of the findings of the present analysis, the thermal treatment tested by the Italian ENEA Research Institute, proved to be a good solution to remove the encapsulant (EVA) from Poly-Si PV panel, allowing the recovery of valuable resources. However, attention should be given to the flue gas treatment, because if they are not properly handled, they may release heavy metals (Tammaro et al., 2015) and fluorinated compounds resulting from the incineration of the plastic layer in PVF (Huber et al., 2009). Furthermore, in order to optimize the recovery process, future research is needed to modify the module design, for example by limiting the use of plastic polymers in their composition. In this way, also the dependence of the PV chain on fossil fuels would be decreased. An important consideration relates to the source of energy required for the thermal process. The analysis of the Italian electricity mix, has pointed out that its larger component comes from fossil fuels (about 70%); moreover, the main impacts are generated by the disposal of tailings from fossil fuels extraction and refining processes.
The existence of a waste generating process upstream of the actual PV treatment/recycling process lowers the whole performance. As a consequence, not only an improvement of the efficiency of the thermal treatment process is needed, in order to decrease the electricity demand, but also an improvement of the electricity supply chain, with a larger share of renewable energy sources, would contribute to a more sustainable processing. This would act as a feedback, with renewable sources supporting the environmentally sound management of renewable power devices.




| | GWP | TAP | FEP | HTP | POFP | TEP | MDP | FDP |
|---|---|---|---|---|---|---|---|---|
| High-rate recovery scenario | -7.8E-03 | -1.7E-02 | -1.1E-01 | -6.7E-02 | -5.3E-03 | -9.3E-04 | -2.9E-03 | -1.3E-02 |
| Low-rate recovery scenario | -2.0E-03 | -7.0E-03 | -3.3E-02 | -2.8E-02 | -2.1E-03 | -3.0E-04 | -4.4E-04 | -2.2E-03 |

**Figure 3.** Recipe midpoint (h) normalized impacts calculated for high-rate and low-rate recovery scenarios, with reference to 1 $m^2$of c-Si PV panel. Results include avoided impacts due to recovery of energy and material flows.

Furthermore, the targets of the WEEE European regulation should be revised in order to prioritize a quality material-related approach over a raw mass-related one (Reck and Graedel, 2012). In fact, the recovery/recycling of aluminum and glass only would be sufficient to meet the legislative objectives of recovery/recycling in terms of mass recovered (80% recovery prescribed), but revenues would not be able to cover the high costs of logistics and treatment (Cucchiella et al., 2015). Conversely, this would happen if all high value components are recycled, through the additional recovery of silicon, silver and copper, thus increasing both the economic and environmental benefits (Bio Intelligence, 2011).

## *Conclusion*

A careful analysis of the environmental impacts of a photovoltaic installation cannot be limited to considering only the production and operational phase of the PV panels, but the whole life cycle has to be considered, including the impacts associated with the "end-of-life" phase, related to their decommissioning and recycling. Moreover, with regard to the entire cycle of the production chain, an efficient recycling of the PV panels at the end of their life can decrease the impacts associated with their production. This study has presented the preliminary results related to the evaluation of environmental impacts of an innovative recovery process of crystalline silicon photovoltaic panels, using Life Cycle Assessment methodology. The analysis demonstrated that the recovery process of the c-Si PV panels shows significant environmental benefits in all impact categories considered and especially freshwater eutrophication, human toxicity, terrestrial acidification and fossil depletion. In particular, the advantages gained by the recovery of silicon and aluminum leave plenty of room for future research in the field of EoL PV panels management.

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# CHAPTER 8 – FOOD CHAIN

## A survey on the energy sustainability of urban agriculture towards more resilient urban systems

*Introduction*

Food is the primary energetic need for humankind. Today, approximately a billion people are chronically malnourished, while our agricultural systems are concurrently degrading land, water, biodiversity and climate on a global scale (Smith 2013). So, the challenge of guaranteeing food security for 9 to 10 billion people by 2050, and doing it sustainably, is considerable. Food security, according to the World Summit on Food Security, is defined as existing 'when all people at all times have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life. The order of magnitude of a human's energetic needs, which must be supplied from food, is of $10^2$ W calculated on a daily basis (Casazza 2012). The use of power (watt) here depends on the fact that each energy cycle has different timescales (e.g.: the human metabolic cycle is calculated over a day, while a vegetative cycle related to fruit/vegetables growth has a year timescale, and so on). This is why it is better to use power instead of actual energy. Actually, the world agriculture produces enough food to provide every person with more than 2700 Calories per person per day, according to the most recent estimates (FAO 2010[23]), thanks to the introduction both of agricultural technologies and of chemical fertilizers. We can state that, in a very real sense, we are literally eating fossil fuels.

While nearly 40% of the terrestrial photosynthetic capability has been appropriated by human beings just for agriculture (Vitousek et al. 1986), the Green Revolution increased the energy flow to agriculture by an average of 50 times the energy input of traditional agriculture, and, in the most extreme cases, by 100 fold or more (Giampietro and Pimentel 1994). Nonetheless, while energy input has continued to increase, a corresponding increase in crop yield hasn't been observed (Pimentel and Giampietro 1994). This energy requirement does not include the energy to produce the machinery, or to transport process and package the resulting food.

Whilst agriculture is a prime user of energy, it is also a major contributor to climate change, which may make food security even more difficult to attain (FAO 2010). Climate change, through increasing variability of the weather, may also undermine the stability of whole field-to-fork chain. There needs to be a considerable investment in

[23] FAO, Agriculture and food security: http://www.fao.org/docrep/x0262e/x0262e05.htm

adaptation and mitigation actions toward a "climate-smart food system" that is more resilient to climate change influences on food security (Wheeler and von Braun 2013). It is known that food security has always been an important aspect of urban resilience (Barthel and Isendahl 2013).

Historically, cities relied on the agricultural production of the local countryside (Pons et al. 2015). In the last century the diffusion of modernist ideology, the innovations in food transportation over great distances and agricultural industrialization lead to break the relationships between cities and its countryside for food provision. This implied the abandonment of virtuous and vital energetic cycles, and the increasing marginalization of agriculture (Marchetti et al. 2014; Folke 2004). Moreover, urbanization and counter urbanization contributed to expand the city towards the periphery and countryside into smaller and less densely populated development clusters within the city region: the so called urban sprawl, that is still ongoing (Cavallo et al. 2016; Dielman 2016; Lupia and Pulighe 2015; Marchetti et al. 2014; Vermeiren et al. 2013; Sanjé-Mengual et al. 2012; EEA, 2006). Negative effects of these patterns are land consumption and soils sealing, that involve the conversion of more fertile and well positioned lands located near the cities, the coasts and in the plains (Marchetti et al. 2014; European Commission, 2011). However, in the last decade there is a renewed interest towards rural environment (Marchetti et al. 2014) and its values (Henke et. al 2015; Torquati and Giacchè 2010) and towards the relation between agriculture and the city. In this framework there is also an increasing development of urban agriculture in a variety of forms (Henke et al. 2015; Rete rurale 2014; Orsini et al. 2013). This interest evidences the need, on one side, of a sustainable planning and living of the city and, on the other side, of food systems more in accordance both to the specificity of territories and to the needs of current way of life (Sommariva 2012).

This study reviews the literature related to urban agriculture, with the aim of deepening environmental and socio-economic impacts of urban agriculture as well as energy use and energy efficiency aspects with respect to food production for cities. Our final goal is evaluating to what extent urban agriculture can be a strategy for enhancing urban resilience to food security in a sustainable manner and with a positive input-output energy balance (Bojacá and Schrevens 2010; Enriques 2009)[24]. These issues are conceptualized within the wider framework of city-countryside relationship. This approach offers an alternative view to the analysis of resilience of urban population to food. The continuous elaboration of that framework is useful for understanding the evolution of land use change in response e.g. to urbanization or changes in social and economic systems (Henke et al. 2015; Sommariva 2012). Key factors as land owned make urban dwellers resilient to food security shocks and stresses (FAO 2016).[25]

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[24] **Urban resilience** is defined as the "capability to prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to public safety and health, the economy, and security" of a given urban area.

[25] http://www.fao.org/docrep/013/al920e/al920e00.pdf

*Material and methods*

The literature proposes different definitions of UA. Each one focuses on some aspects (as types of UA activities carried out, types of goods produced under UA as well as location of the UA activities) (Smit et al 2001) and specific aspects. Miccoli et al. (2015) note that UA definitions evolved over time encompassing further aspects within UA framework such as multifunctionality, safety and food justice issues. Moreover, as UA groups a wide array of forms, activities and goods and services produced it is difficult to find a unique definition. We propose an integration of some definitions for covering better the scope of our study. FAO and UNDP (2001) in the Report: Food, Jobs and Sustainable Cities (1996) defines UA as: *"an industry that produces, processes, and markets food, fuel, and other outputs, largely in response to the daily demand of consumers within a town, city, or metropolis, on many types of privately and publicly held land and water bodies found throughout intra-urban and peri-urban areas. Typically urban agriculture applies intensive production methods, frequently using and reusing natural resources and urban wastes, to yield a diverse array of land-, water-, and air-based fauna and flora, contributing to the food security, health, livelihood, and environment of the individual, household, and community.* According to this definition UA is classified as an industry and involves activities performed on a large scale excluding e.g. small urban farming. Instead, the definition of Mougeot & Centre (2006) even more generic concentrates on the main activities of UA as: "*the growing, processing, and distribution of food and non-food plant and tree crops and the raising of livestock, directly for the urban market, both within and on the fringe of an urban area*" (Mougeot & Centre, 2006, p. 4). On the other side it lacks information about the method used to carry out UA's activities and its potential benefits as indicated in the first definition of FAO and UNDP.

The literature search has been performed trough Web of Science[26] and Science Direct[27], using different keywords such as urban agriculture, urban agriculture and energy, urban agriculture and sustainability, energy impacts of urban agriculture, costs and benefits of urban agriculture, community gardens, urban farming. We limited our search to the articles published in the last six years. The other main criterion for the selection of relevant studies has been the topic covered by the studies (environmental, social and economic impacts of UA, energy impacts of urban agriculture, UA production systems, UA and urban policies within the broader framework of city-countryside or urban-rural relationship). At the end we selected 55 articles. They are listed in the Appendix. Some of them are review of the existing literature (Lin et al. 2015; Poulsen et al. 2015; Middle et al. 2014; Mok et al. 2014; Orsini et al. 2013; Guitart et al. 2012; Rowe 2011; McCormack et al. 2010) while the others are case studies using different method of analysis: survey, energy analysis, life cycle assessment, etc.

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[26]http://apps.webofknowledge.com/UA_GeneralSearch_input.do?product=UA&search_mode=GeneralSearch&SID=S1ZgHNmPtCOpDKS7hpe&preferencesSaved=

[27] http://www.sciencedirect.com/science/search

*Energy use in food production*

Food provides energy and nutrients, but its acquisition requires energy expenditure (mainly fossil energy) in all phases of the life cycle of agri-food products as in the production of crops and dairies, in post-harvest operations, food storage and processing, food transport and distribution, and food preparation (FAO 2012; Roy et al. 2009). The consumption of fossil energy in the life cycle can be divided in two categories: direct and indirect. Direct consumption of energy refers to the consumption of fuels for operating machineries, irrigation pumps, heating greenhouses and the moving loads, the consumption of electricity for drying crops, heating and illumination. Indirect consumption of fossil energy refers to the energy spent in the industrial sector for the production of the technological inputs used in agriculture. This indirect consumption includes the production of fertilizers and pesticides (in the chemical sector), the fabrication of machinery (in the mechanical sector) and the fabrication of other infrastructures. For this reason, it is normal to find a discrepancy between the estimates of energy consumption of the agricultural sector found in national statistics and the estimates based on the accounting of direct and indirect fossil energy consumption, which also include the embodied energy of the technical inputs (Arizpe et al. 2011; Ghisellini et al. 2015a, b).

*Cities, food and energy dependence*

Modern cities almost exclusively rely on the import of resources to meet their daily basic needs. Food and other essential materials are transported from long-distances, often across continents, which results in the emission of harmful GHGs (Grewal and Grewal 2012). This problem, even if with a different dimension, already existed in more ancient times. A simple example with respect to the city of Rome (Italy) in the beginning of the ancient imperial period (referred to 2.000 years ago) illustrates the problem of external food dependency. Let us consider wheat caloric content ($1.69*10^7$ J/kg), ancient mean wheat productivity of 1.5–2 t/ha (Jacobsen and Adams, 1958), the 1-year cycle as reference (one harvest per year for wheat) and the fact that an adult man body requires a mean daily food energetic intake of 2.200 kcal (Doughty and Field 2010). The ancient city of Rome (in the early imperial period) had a surface of $7.0*10^7$ $m^2$ and about 1 million inhabitants. The energetic (metabolic) need for feeding the inhabitants of the ancient city of Rome in 1 year was $3.36*10^{15}$ J (this number is obtained multiplying the energetic need of 1 man for 1 year for the number of inhabitants of the ancient city of Rome). Considering the available data, it is possible to derive that a surface of $1.13*10^9$ $m^2$ (equivalent to 16 times the surface of Rome at that time) would have been necessary for feeding the ancient city of Rome. This simply means that the city of Rome had to rely on external resources for food production and for the survival of its inhabitants. This was energetically costly. The main energy cost was related to food storage and transport (e.g.: granaries, transportation through ships and carriages, working animals and even slaves). On the other side, two case studies from widely different historical and cultural contexts – the Classic Maya civilization of the late first millennium AD and Byzantine Constantinople – demonstrate that urban farming is a pertinent feature of urban support systems over the long-term and global scales. Urban gardens, agriculture, and water management, as well as the linked social–ecological memories of how to uphold such practices over time, have contributed to long-term food security during eras of energy scarcity (Barthel and Isendahl 2013).

At a time when most of the world's population lives in cities, new issues of physical and financial access to food are raised, together with the recent emergence of a 'New Food Equation', marked by food price hikes, dwindling natural resources, land grabbing activities, social unrest, and the effects of climate change. The present diffusion of technologies and the globalization of the markets have reduced further the distances between cities and global food systems, increasing, in some terms, their resilience to possible food shortages, mainly due to their connectivity to higher and global food markets (Barthel and Isendahl 2013). However, since cities today mainly rely on food imports transported from long-distances, the result is an increasing exposure of cities to sudden severance of supply lines, caused by oil peak scenarios and to higher emissions of harmful greenhouse gases (Grewal and Grewal 2012).

*Increasing urban resilience: agriculture into the city*

Despite the current increase of competition for natural resources (e.g. soil, water, energy) between city and countryside, it is observable the abandonment of the idea of "country" as an obsolete sector in favour of its revalorization from a productive and cultural point of view (Torquati and Giacchè, 2010; Toccaceli 2010). This new orientation clearly reflects itself in the definition of "rural and urban relationships" compared to "city and country relationships" for the purpose of highlighting the positive values the society attributes to the rural environment and to the multiple benefits it is able to provide (Torquati and Giacchè, 2010). Most importantly this fact evidences the need of relaxing the conflict between city and country to meet the goal of sustainability that requires a balance between the economic development (centred in the city) and ecosystems bio-capacity (centred in the country) (Iacoponi 2004). The end of dualism between city and country in favour of a better integration is progressively suggested in different policy documents of European Union starting from the Alborg Charter (1994) of European Cities &Towns towards sustainability, with the advent of Rural Development policy (Council Regulation, EC, No 1257/1999); the second pillar of Common Agricultural Policy and with the Assembly of European Regions (AER 2008; Iacoponi 2004; Torquati and Giacchè 2010).

The reintroduction of agriculture into the city responds to the search for synergistic relations as just above mentioned. It is also advanced through local policies aiming to improve the environmental and social sustainability as well as within spontaneous informal initiatives of citizens (Lopez 2014). The reintegration of agriculture within the urban environment has a great potential as evidenced by Folke (2004) who proposed the term "ruralisation" to emphasize the importance of this new orientation. Agriculture within the urban environment makes cities much more food resilient and less vulnerable to food shocks (Folke 2004).

Furthermore, the establishment of local food systems leads to organizational efforts either at the local level or in the form of geographically centralized networks, which allow energy expenditures linked to distribution to be minimized (Mundler and Rumpus 2011). Positive side effects, while considering an energetic perspective, can also be recorded in the case of rooftops planted with plants, which also contribute to the house thermal insulation and reduce the energy required for cooling the house (Orsini et al. 2013). Agriculture has been incorporated into urban expansion plans for different cities, such as Kinshasa, Dar es Salaam, Dakar, Bissau and Maputo. In Lagos and Ibadan, state governments have embarked on urban greening programs involving tree and grass planting in strategic public open spaces including road islands and road setbacks as well as roundabouts. Although the aim is to promote city aesthetics, this practice of policy support has indirect benefits to building resilience for climate change (De Zeeuw et al. 2011).

*Forms of urban agriculture and features*

**Figure 1** shows the different forms of UA evidenced by the selected literature. UA forms are implemented at different scales: at the micro level UA is practiced on green roofs and walls, in backyards and along streets. At the meso level UA consists of community gardens, individual allotments and urban parks while at the macro level the practiced forms are commercial farms, nurseries and greenhouses. At all three scales public, private or cooperative forms of ownership co-exist and aimed by different intentions (Cretella and Buenger 2016).

Private gardens produce vegetables and fruits for private consumption. "*Such gardens do not always allow for maximum use of available space or have ideal conditions for growing food, such as full sun or the appropriate soil type; these gardeners are simply growing food in the space available in their backyards*" (Codyre et al. 2015). In the city of Rome (Italy), UA is mainly concentrated within the urban area delimited by the highway ring (Grande Raccodo Anulare). In this area some Authors evidence the existence of residential kitchen gardens managed by farms and citizens. They produce orchards, mixed crops, olive grows, horticulture and vineyards (Cavallo et al. 2015; Lupia and Pulighe 2015).

Within UA cropping and livestock activities are included (Liang et al. 2013). Cropping activities are more practiced than livestock activities and horticulture seems the most dominant component as in the case of many West African cities of Burkina Faso, Benin, Nigeria, Niger, Mali and Ghana (Orsini et al. 2013). In urban horticulture the adopted crop production systems depends on the local culture and traditions. However, within cities are recommended the growing of short cycle and highly perishable crops and in peri-urban areas the adoption of production systems devoted to medium or long cycle crops and orchards (Orsini et al. 2013).

Contrary to private gardens that are mainly managed by families, community gardens involve members of a local community and the production of food and flowers in open spaces (Guitart et al. 2012). The American Community Gardening Association defines them as "*any piece of land gardened by a group of people*" (McCormack et al. 2010). Guitart et al. (2012) reviewed 89 articles published in the last decade and dealing with community gardens located in countries as USA, Australia, Canada, UK, South Africa, etc. and found that community gardens are mainly operated by non-profit organisations including cultural and neighbourhood groups and schools. Community gardens are not only created for growing plants for nutrition and economic benefit, but also to "*satisfy local needs for contact with nature, education, civic activism and neighbourhood renewal"* (Middle et al. 2014). Their agricultural practices are more similar to bio-intensive high production farming than to conventional agricultural practices (Algert et al. 2014). This reflects the strong civic content of this form of UA that in turn is an example of implementation of civic agriculture (Chen 2012). The term "civic agriculture" originates from Lyson (2007) who studied the counter trend towards localization of agriculture and food production in the U.S. versus the current industrialized and globalized American food and agricultural system (Chen 2012).

Urban farms refer to local production of agricultural food for the market (Golden 2013) or the people of a community (Longo 2016). As showed by the case study of Lafayette (California) documented by Longo (2016), urban farmers arise in response to the unsustainability and globalized nature of agro-food systems. The main goal is to build a local food system and increase the development of a community. At the distribution point farmer's markets are recurrent markets with fixed locations where local farmers sell a wide variety of farm produced locally (Golden 2013; McCormack et al. 2010).

Adinolfi et al. (2013) analysed green spaces functioning and benefits. Urban green spaces includes parks, gardens, open corridors and wooded walking areas and are a key element of modern urban design (Adinolfi et al. 2013; Lafortezza et al., 2013; Bennett and Mulongoy, 2006). They focus on the interaction between man, the environment and biodiversity (Adinolfi et al. 2013; Feng et al, 2005) and provide provisioning, regulating and cultural services (Middle et al. 2014). Some of these important functions have an economic value (Adinolfi et al. 2013). The establishment of urban food trees within parks and other urban public green areas is gaining attention and showed to be a viable financial investment under certain conditions for a municipality in Peru and their local inhabitants (Lafontaine-Messier et al. 2016).Urban food trees produce seeds, fruits, leaves, forage or other edible goods (FAO, 2001). The use of food trees as part of urban forestry programs is considered as a tool for the creation of multifunctional urban public green areas (Lovell, 2010). The same is for street trees which primary purpose is changed in the last 30 years shifting from role of beautification and ornamentation to the one that also includes the provision of services such as storm water reduction, energy conservation and improved air quality (Mullaney et al. 2015; Seamans, 2013).

UA also includes the peri-urban agricultural areas around cities and towns. These areas that are subject to a great urban pressure and provide a relevant fraction of products and multifucntional services to the urban local population (Dielman 2016; Henke et al. 2015; Pribadi and Pauleit 2015; Lin et al. 2015; Zasada 2011; Bojacá and Schrevens 2010; Mougeot, 2010). The type and intensity of agricultural practices influence the peri-urban landscape and the social, aesthetic and environmental functions of neighbourhood urban agglomerations (Zasada 2011).

Some studies deal with the adoption of UA forms within city buildings as vertical farming, green roofs and rooftop greenhouses (Sanyé-Mengual et al. 2012; Rowe 2011). Vertical farming applies the concept of UA within a building that could be devoted only to urban farming or to urban farming, residential, commercial and other urban purposes (Al-Chalabi 2015;Torregiani et al. 2012)[28]. Fruits, vegetable and grains can be produced inside the building in a city or an urban centre by applying different systems: unprotected crops in roofs; protected crops in the walls of skyscrapers and protected crops in roofs using hydroponics (water with nutrients) (Al-Chalabi 2015; Sanyé-Mengual et al. 2012). Green roofs and green walls involve the growing of plants on rooftops or facades partially replacing the vegetation destroyed with the construction of the building (Lehmann 2014; Rowe 2011). They can be established for agricultural and decorative purposes (Lin et al. 2015). Green roofs and walls are considered solutions for mitigation the urban heat mitigation at low cost and for cooling buildings through their insulation effect reducing energy transfer into buildings (Lehmann 2014). However, green roofs and walls performances depend on the design and building construction method and seem provide a low contribution to diversity of plant species or animal habitat (Lehmann 2014). Rooftop greenhouses are structures that are integrated into the roof tops of buildings, and protected crops are cultivated by using intensive hydroponic technique (Sanyé-Mengual et al. 2012).

*Energy impacts of urban agriculture*

A few studies investigated the energy balance of urban agricultural forms. Bojacá and Schrevens et al. (2010) for a case study in Bogota evaluated the energy use of peri-urban horticulture and found a negative energy balance (energy output<energy input) for crops as coriander, radish and lettuce. Spinach resulted the most planted crop and the only one with a positive energy balance. Al-Chalabi (2015) analysed the amount of energy required to a building designed for vertical farming and its capacity to meet with renewable energy the onsite demands of the building. The energy is needed indoor for lighting for plant cultivation and pumping water and is generated from a solar panel installed on the roof and the facade. The results evidence that in areas with abundant sunlight vertical faming is energy feasible and solar panels generate enough energy for lighting and pumping.

[28] http://www.fotovoltaicosulweb.it/guida/vertical-farm-la-rivoluzione-sostenibile-dell-agricoltura-urbana.html

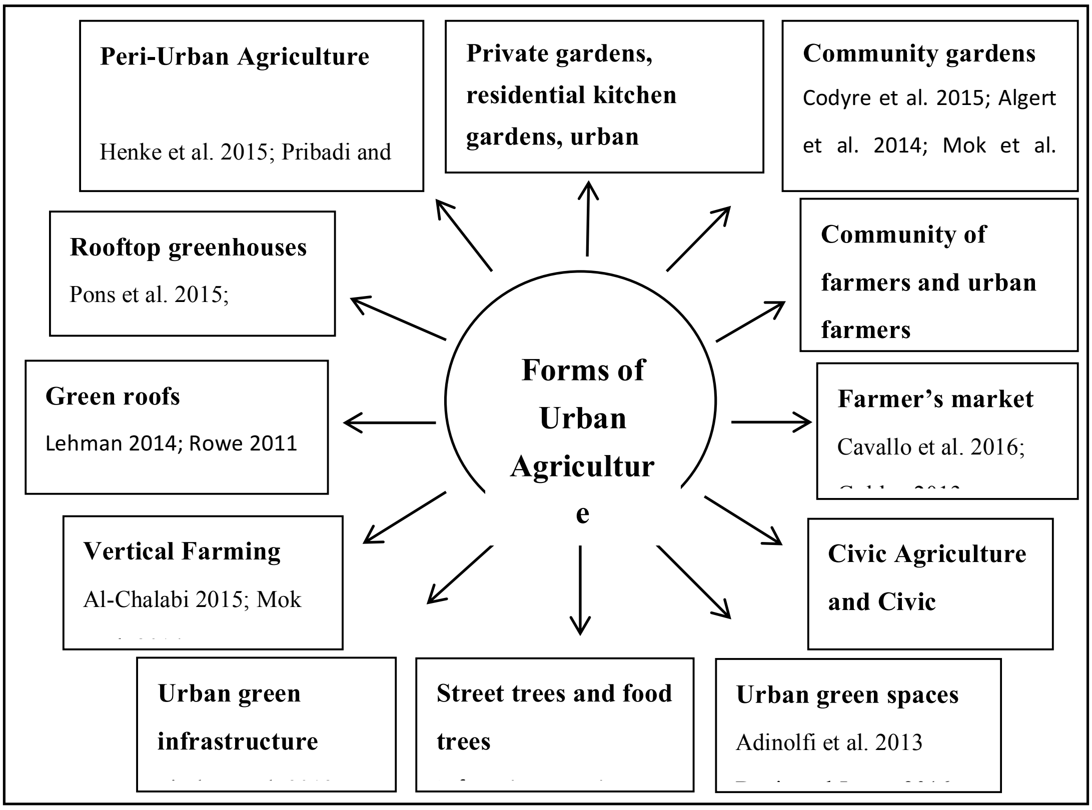


**Figure 1**. Selected literature classified according to the form of urban agriculture investigated

Goldstein et al. (2014) reviewed the results of a report analysing the energy benefits of integrating a rooftop greenhouse cultivation system in a building. The energy can be reduced by 41% in northern climates. In Mediterranean conditions for another rooftop greenhouse (cultivating tomatoes using a Hydroponic system) installed in a building in Barcelona (Spain), higher potential energy savings up to 74% are calculated by means of LCA. In this study energy savings are obtained by comparing the rooftop greenhouses with the current scenario where tomatoes are produced outside of Barcelona and transported to the city where they are consumed.

Finally Mullaney et al. (2015) argue that many Authors investigated potential energy savings provided by planting street trees. For example a 10% increase in tree cover can reduce total heating and cooling energy use by 5–10% (US$50 to $90) (McPherson et al., 1994). In fact, a single tree can decrease annual heating costs by 1.3% and cooling costs by 7% (McPherson et al., 1994). Case studies in USA such as in Sacramento (California) showed that trees planted on the west and south sides of houses (USA) reduced summertime electricity use by 185 kW h (5.2%) per household (Donovan and Butry,2009), and trees in Auburn (Alabama), reduced summer energy use by 3.8% compared with houses with no shade (Pandit and Laband, 2010). Electricity consumption was found to decrease by 1.29 kW h/day for every 10% of shade coverage (Pandit and Laband, 2010).

*Environmental impacts of urban agriculture*

Urban agriculture in its different forms can provide an important contribution to the sustainability and liveability of the city (Mullaney et al. 2015; Ackerman et al. 2014; Adinolfi et al. 2013; Orsini et al. 2013). Urban farms, community gardens, green roofs and green walls reduce urban heat island effects limiting the use of air conditioning, mitigate urban storm water impacts, and lower the energy embodied in food transportation (Ackerman et al. 2014; Lehman 2014). Reducing the distance that food travels also decline the amount of food waste (Pons et al. 2015). Urban agriculture may also improve nutrient cycling through local recycling and re-use of organic and water wastes (Orsini et al. 2013; de Zeeuw et al., 1999), reducing the ecological footprint of urban centres (Peters et al., 2009; de Zeeuw et al., 1999). Ackerman et al. (2014) evidence cases in New York of many rooftop farms that use the compost made from locally collected food scraps, For example the Intercontinental New York Barclay hotel, uses food scraps from the kitchen of the building (IHR, 2013). Rooftop greenhouses can be designed to use waste heat, waste water and $CO_2$ flows of the building. Beyond these benefits the food supply with rooftop greenhouse reduce transport requirements, allows the re-utilisation of packaging and reduction of product losses being a local and fresh system of production (Pons et al. 2015; Sanyé-Mengual et al. 2012). Compared to the current agri-food system of production and distribution the production of 1 kg of tomatoes in rooftop greenhouses showed for a case study in Barcelona to reduce the environmental impacts to several impact categories such as ADP, AP, EP, GWP, ODP, HTP, CED[29] (Sanyé-Mengual et al. 2012). In a subsequent pilot study in Barcelona the environmental impacts to GWP and CED of the life cycle of 1 kg of tomatoes resulted lower than a multi-tunnel greenhouses both in the production stage (cradle to grave) and up to the consumption stage (cradle to consumer). The retail price resulted lower for RTG. The environmental impacts of the rooftop greenhouses structure resulted higher compared to the multi-tunnel greenhouses mainly due to indirect impacts of the materials used and to the maintenance of RTG structure. The life cycle economic costs of RTG structure also resulted higher compared to the multi-tunnel greenhouses (Sanyé-Mengual et al. 2015).

The expansion of green spaces under urban agriculture improves cities' microclimate, contributes to biodiversity conservation increasing the quality and quantity of ecosystems services and to the requalification of underutilized and degrades lands (Lin et al. 2015; Fischer et al. 2013; Orsini et al. 2013). In the peripheries UA connect the city to the countryside. However, UA activities should be properly managed as in some cases they provide disservices as water upon and below the ground, for the uses of fertilizers, pesticides, and animal discards (Lin et al. 2015; Orsini et al. 2013). The case study of Chinese livestock sector in the municipal area of

[29] ADP: Abiotic Depletion Potential, AP: Acidification Potential, EP: Eutrophication Potential, GWP: Global Warming Potential, ODP: Ozone layer Depletion Potential, http: Human Toxicity Potential, CED: Cumulative Energy Demand

Beijing (China) showed that GHG emissions of livestock sector reduced from 2007 to 2009 revealing that the policy measures adopted to modernize urban agriculture has made some progresses. However, the current agricultural land area was found to be insufficient to consume the total amount of livestock waste suggesting the need of adopting additional measures to reduce GHG emissions of livestock and the pressure on agricultural area such as the development of biogas industry (Liang et al. 2015).

Other benefits cited by the literature regards e.g. street trees as they reduce storm water runoff, improve air quality, carbon sequestration, provide shade, and mitigate the urban heat-island effect enhance biodiversity by providing food, habitat and landscape connectivity for urban fauna (Lin et al. 2015; Mullaney et al. 2015; Adinolfi et al. 2013). In many cases green spaces offer the only contact with nature in the urban environment (Adinolfi et al. 2013).

*Economic impacts of urban agriculture*

Generally, people engage in urban agriculture for satisfying three main goals: community development, food and economic security (Poulsen et al. 2015; Ackerman et al. 2014). Food security is of particular concern mainly in developing countries even the issue is also worsening in developed countries due to the present prolonged economic crisis (The Guardian 2014). Food security can regard both the "*quantity and quality of food available to a household".* In turn food insecurity can be temporary or chronic and be caused by many factors with a higher incidence in adolescents compared to young children (Ackerman et al 2014). In developed countries food security is also linked to increasing health problems as obesity and diabetes (Corrigan 2011). In USA about 15% of all residents cannot afford quality food due to insufficient financial and other resources (Corrigan 2011). Community gardens in Baltimore city contribute to alleviate quality food problems as they assure a constant supply of fresh fruits and vegetables enhancing food security of individuals, households and the community (Corrigan 2011). Community gardeners contribute to the development of more healthy diets as participants consume more fresh fruits and vegetables and less sweet foods and drinks, compared with non-gardeners (Guitart et al. 2014; Blair et al., 1991). School community gardens can be considered an innovative public health intervention as showed by some Australian case studies. They increase knowledge of and access to different type of health-giving fruits and vegetables. For this reason school community gardens can be considered a potential means for the conservation of agro-biodiversity and the enhancement of diet and health and well-being of their urban school children (Guitart et al. 2014).

The adoption of different forms of UA as farmer's market, community gardens, urban horticulture, peri-urban agriculture demonstrated to increase the quantity and quality of food available for low income urban households in different geographical and social contexts (Poulsen et al. 2015; Warren et al. 2015; Mok et al. 2014; Orsini et al. 2013; Monachie et al. 2012; Corrigan 2011; de Zeeuw et al. 2011; McCormack et al. 2010). Moreover the participation to farmer's market and community gardens programs in USA is associated to a greater intake of fruits and vegetables (Mc

Cormack et al. 2010). Even if the important role of community gardens some Authors evidence that they cannot resolve food insecurity (Corrigan 2011).

The role of peri-urban agriculture in food production is highlighted by many Authors (Dielman 2016; Henke et al. 2015; Zasada 2011). For example in Mexico City 20% of its food mainly comes from peri-urban agriculture. Important local crops are also sources as nopal, maize, tuna (fruit) and amaranth (Dielman 2016). UA potential capacity is also investigated both in developed (Montréal, Guelf, Cleveland) and developing countries at different scales (Badami and Ramakutti 2015; Codyre et al. 2015; Haberman 2014; Orsini et al. 2013; Grewal and Grewal 2012). In low income countries according to Badami and Ramakutti (2015) the potential seems low or infeasible (in particular in countries with large population and high fraction of poor as well as with high urban densities) due to the insufficient availability of land in urban areas. This fact evidence the relevant problem that face a further development of urban agriculture to meet its potential production (Codyre et al. 2015) as land availability is the highest limiting factor to production in and around cities (Orsini et al. 2013) As a consequence some Authors suggest a sustainable intensification of crop production (more than four harvests per year) and cultivation of high value crops in cities (Orsini et al. 2013; De Bon et al. 2010). Finally Poulsen et al. (2015) note that agricultural production fluctuates by season and there are cases as in Zimbabwe that only for some months (1-3 months) UA provides sufficient produce for household consumption.

UA and peri-urban agriculture improves economic security as it is a source of income for many urban poor (Poulsen et al. 2015; Monachie et al. 2012). In a study involving some African countries, only considering farming households the percentages of household income from UA ranged from 3% to 71% across countries and the percentage was greater than 44% in two countries: Madagascar (63%) and Nigeria (71%). Widening the sample to both farming and non-farming households, the percentages of households that derived at least 30% of their income from UA were high in all four of the African countries, ranging from 18% (Malawi) to 24% (Nigeria) (Poulsen et al. 2015). Orsini et al. (2013) evidence that urban horticulture generates higher incomes than other farm-related activities as showed the case of vegetable peri-urban production in Ho Chi Minh (Vietnam) where the net daily income from a vegetable-grown hectare was equal or higher than twofold as compared to rice, and provided employment levels at least five times higher (Jansen et al. 1996). This is also the case of peri-urban areas of Jabodetabek Metropolitan Area (JMA) including Jakarta (Indonesia) where peri-urban farmers have been able to compensate the declining agricultural land base through the development of more profitable farming activities such as horticulture or inland aquaculture (Pribadi and Pauleit 2015). In other countries as Mexico UA the agricultural activities of peri-urban zone does not provide sufficient income to farmers and need additional means of incomes (Dielman 2016).

UA also allows reducing the costs of food purchase (Monachie et al. 2012). It is estimated that urban poor spend between 60 and 85% of their income just to feed themselves (Orsini et al. 2013; Redwood 2008). The slum dwellers, which grow their own food, can provide food for their families reducing the costs of food purchase (Orsini et al. 2013).

Experiences cited in the USA evidence savings from the development of urban agriculture ranging from $475 (for individual gardeners) to $915,000 for an entire community garden program (Golden 2013). Community gardens in San Jose (California) produced on average 2.55 lb/plant and saved $435 per plot for the 4-mounth season (Algert et al. 2014). However, as a matter of fact, with few exceptions, a clear negative correlation between participation in agricultural activities and level of welfare has been noted (Zezza and Tasciotti 2010).

Urban farming also creates job opportunities (Agbonlahor et al. 2007) and stimulates the growth of enterprises in the related activities (e.g., farming inputs, food processing, packaging, marketing, etc.) (Orsini et al. 2013). Although urban agriculture does not appear to be the major urban economic activity, in a number of countries, there is a significant share of the urban population that derives income on the production of crop and livestock products (Poulsen et al. 2015; Zezza and Tasciotti, 2010). Urban agriculture is eminently an activity practiced by the poor, and, with the rise of food demand in cities, small-scale farming gradually shift from subsistence farming to commercial farming (Dossa et al. 2011). Urban agriculture is a catalyst for new businesses, as in the case of food justice projects or social gardens (Ferreira et al. 2013; Golden 2013). For example, in the USA some community food projects financed by the USDA contributed to the creation of 2,300 jobs and over 3,600 micro firms while 35,000 farmers were trained within community projects on sustainable agriculture, business management, and marketing (Golden 2013).

*Social impacts of urban agriculture*

Urban agriculture is largely recognized as a means for intensifying social relationships. For example community gardens provide opportunities to community residents for gatherings and socializing (Golden et al. 2013; Mullaney et al. 2015) breaking down barriers, promoting friendships (Patel 1991), sharing consensus around decision making and planning processes. UA has also the potential to increase the empowerment of urban communities (Golden 2013; Ackerman 2014; Mullaney et al. 2015). It is suggested as a viaticum that encourages the progressive transition towards participative democracy that is a key element of sustainable development. In this sense the urban planning and space can be seen as the result of a conflictual and at the same time collaborative process between public authorities and institutions, citizen's movements and informal groups (Golden 2013; Lopez 2014).

Other social benefits of UA concern the aspects of food producing and procurement in unserved areas (Mees and Stone 2012) as well as the benefits to the safety of urban places by reducing their exposure to vandalism and crime-ridden (Golden 2013; Mullaney et al. 2015). In fact, building areas with a high level of trees reduce the incidence of crimes compared to areas with low levels of vegetation. In turn well maintained vegetation creates a sense of community care among residents (Mullaney et al. 2015).

UA activities in American community and commercial farms and community gardens offer the opportunity of enriching education in terms of health food, skill development, job skill training and leadership experiences for young people, including the development of awareness on environmental issues and ethics, sustainability and food systems (Bregendahl and Flora, 2007; Kerton and Sinclair, 2009; Travaline and Hunold, 2010; Golden 2013; Orsini et al. 2013; Cohen and Reynolds 2014). Finally UA promotes cross generation between youths and seniors (Armstrong, 2000) as well as health improvement and cultural integration (Golden 2013; Orsini et al. 2013). Urban farms and community gardens works as reintegration projects of immigrant communities involving the production of food for their own use, their selling or sharing (Fredrich, 2013; Golden 2013; Ackerman 2014). These programs create the opportunity for immigrants to connect with other immigrants and with the society (Golden 2013).

*Urban agriculture's role in planning urban resilience*

Urban and peri-urban agriculture is increasingly being promoted as a multi-focal strategy for enhancing urban food security and advancing climate change adaptation and mitigation efforts in cities. The extent to which this potential can be realized is circumscribed by access to adequate land and water resources, the degree of recognition of urban and peri-urban agriculture within the urban policy domain, and the ability of producers to effectively navigate the myriad risks associated with food production in urban and peri-urban environments (Padgham et al. 2015). Many cities have sustainability plans, but have not specifically addressed urban resilience, or, if they have, often conflate or uses sustainability and resilience interchangeably (Redman 2014). Resilient supply of non-disaster related ecosystem services, among which local food and water production are included (Gómez-Baggethun et al. 2013), provided within urban areas has received little attention. Though some cities are beginning to consider how ecosystems in cities can help mitigate climate change effects or create spaces that increase existing adaptive capacity for post-effect recovery, in most global cities services provided by urban ecosystems remain poorly connected to urban planning, design, and management for resilience (Scarlett and Boyd 2013). Policy and planning regimes organize the processes of strategies formulation and goal selection that guide which and how urban ecosystem services are considered (Hansen et al. 2015). Currently, there is limited knowledge on such planning processes, with their own historical timelines and path-dependencies as well as their context-dependent drivers and barriers relate to and impact aspects of ecosystem services related to urban resilience or the uptake of urban ecosystem services and resilience concepts in governance practices (Wilkinson et al. 2013; Erixon et al. 2014; Frantzeskaki and Tilie 2014). Understanding and addressing resilience through and of urban ecosystem services may enable urban planning and governance to become adaptive and reflexive not only to external drivers (e.g. climate change extremes and vulnerabilities) but also to internal drivers. The health and wellbeing of urban residents depend on locally produced ecosystem services. Resilient supply of those services in the face of global environmental and other changes is important to achieving sustainability goals being set in cities. Additionally, given the large environmental footprints of cities, protection and sustainable use of ecosystems in cities and urban regions are key components of global sustainable development. Resilience focused planning, management and governance will be better served by including ecosystem services explicitly in resilience approaches. However, policy and planning processes are context-dependent with distinct dynamics that affect aspirations for integrating urban ecosystem services and advocating urban ecosystem services oriented planning (de Groot et al. 2010). There is evidence that linking research on urban resilience to urban ecosystem services is an important path way for improving the capacity and efficacy of urban governance for resilience (McPhearson et al. 2014; 2015).

*A possible connecting vision between the urban and the rural world*

The impact of new ideas applied either to planning or to policies depends also on new visions, which should be shared effectively. The vision supports the motivations for a change, partially removing the causes of the existing inertia of any system. In our case, we should not relegate the association of 'landscape' with the rural world. We should, instead, consider the use of connecting terms between the rural and the urban environments, since they are linked with respect to food production and its energy correlates.

Landscape is a connecting term, which combines incommensurate or even dialectically opposed elements: process and form, nature and culture, land and life (Cosgrove 2006). Frederick Le Play's triad of place, work and folk was graphically expressed by the Scottish architect, ecologist and regionalist Patrick Geddes as the 'valley section', where human activities arise out of organic connections with the land and express themselves in an evolving series of settlement landscapes (Steele 2003). A similar idea was powerfully expressed in Martin Heidegger's 'Building, dwelling, thinking' (Heidegger 1978). A specific aspect of landscape is related to the urban-rural relationship.

Over the last two centuries, the ideology underpinning city-country relationship in urban planning has radically changed, favouring a progressive emancipation and disconnection of the 'city' from its 'countryside' (Elmqvist et al. 2013). From a spatial point of view, this ideology has been articulated in two aspects. The first is still developing under the new concept of 'urban-rural fringe', which started to be discussed from 1937, as "the built-up area just outside the corporate limits of the city" (Pryor 1968). The second one has been related to urbanization channelling. More specifically, the idea of ever growing cities was already developed in the mid-1800s, together with the concept of green belts. The green belt concept goes back to the time of the garden city movement and before. In 1848, Edward Gibbon Wakefield promoted Colonel Light's scheme for Adelaide, Australia, which was based on the understanding that, with the growing size of the city, access to its central area became more and more difficult, owing to increasing traffic congestion. This, in turn, led to the idea that "once a city had reached a certain size, a second city, separated by a green belt, should be started" (Frey 2000). The model of urbanization has been put under discussion, together with its socioeconomic, ecological, cultural and political model (Marchetti 2014), since it omitted both the ecological and social dimensions from the urbanization processes (Elmqvist et al. 2013). The emergence of the city and the countryside as autonomous social entities is mainly a reflection of the diffusion of the modernist ideology, developed at the beginning of the last century from the Chicago School of urban sociology (Barthel and Isendahl 2013), which relied both on the ecosystem theory (Clemens 1916) and on the evidence that the city of Chicago, at that time, well represented the symbol of the city, as the center of innovation and progress. In fact, at the end of 19th Cent., the industry started to overrun Chicago (as well as other cities), changing its previous feature of commercial center surrounded by rural hinterlands. Moreover, with the development of railroad transportation, in the middle of 19th Cent., Chicago also became an important node in the US railroad network, allowing the transportation of food over great distances. The innovations in transport sector have been decisive both in contributing to the development of the ideology of cities separated from their life-support system (countryside) (Wirth 1938) and in excluding the rural aspects of life from the city (Elmqvist et al. 2013). The exclusion accelerated particularly after the World War II, with the industrialization and specialization of agriculture (Mok et al. 2014). This process has been particularly favoured by the availability of cheap fossil fuels, which allowed an increasing surplus of food to be produced and a continuous urban growth worldwide. On the other side, urbanization leads to a continuous expansion of cities towards their rural hinterlands, while the reduced local availability of food (within the cities) has been mitigated by increasing food imports.

Nowadays, in order to talk about the layers of global flows of people, technologies, ideas, money, and ethics that will play a role in shaping the future of food, the term "foodscapes" is used. The urban food question is forcing itself up the political agenda in the Global North because of a new food equation that spells the end of the ‘cheap food’ era, fuelling nutritional poverty in the cities of Europe and North America (Morgan 2014). Future research should investigate how cities can integrate social-practice based approaches into urban planning and design for resilience and sustainability, and how mainstream policy tools such as taxation, financial incentives, zoning incentives, land use regulation or educational programs, can be deployed to foster sustainable and just everyday urban practices (Cohen and Ilieva 2015). This new connecting vision remarks an already existing relation between two environments (i.e. the urban and the rural one). Furthermore, it gives the opportunity of reconsidering the dependencies between these two ‘worlds’. In our specific case, the attention is focused on the production of food and its energetic correlates. Thus, “foodscapes” could well represent a connecting idea to be shared to promote the development of urban agriculture.

*Perspectives*

Results show that urban agriculture plays an important role for the social and economic development of cities addressing partially food needs of urban dwellers and being an

importance source of income in particular in developing countries. The potential of UA depends on different factors and land availability is one of the most limiting factors to its further development. This confirms that urban agriculture is a complementary activity to rural production as suggested by Orsini et al. (2013) and then should be viewed in the wider context of city-countryside or rural and urban relationships.
In the last years the role of urban agriculture increased and evolved in a variety of forms and activities as it is recognized by the studies analysing the multifunctional role of urban agriculture. This aspect is of particular importance for peri-urban agriculture, an area under great urban pressure. Multi-functionality is stimulating the diversification of agricultural activities and the supply of specific products and services to urban dwellers (Henke et al. 2015).
Urban agriculture in its different forms is able to provide many environmental, economic and social benefits being a driver for the achievement of the worldwide objective of sustainable development. For this to happen a careful assessment of on-site environmental and energetic impacts of different UA production forms should be carried out. We have not found studies analysing e.g. energy balance of community gardens or private gardens. This is of a paramount importance for the recognition of urban agriculture as a sustainable production system.

*Conclusions*

Agricultural production is not "the antithesis of the city", but is, in many cases, a fully integrated urban activity. It is important to notice that increasing local food production carries both advantages and social complications. A food system cannot operate in an independent local vacuum, but is integrated within global systems, incorporating both "more alternative" and "more conventional" members and processes, which have to be carefully evaluated (Bellows and Hamm 2001). Nonetheless, the reintegration of agriculture within the urban texture brings many benefits. Among them, a reduction of energy consumption due to avoided or lower transport distances and an increased resilience of the urban communities, together with a sensible beneficial effect on economy, social relationships and health of local communities. Responses to this new biophysical and social geography of food, merged with both philosophical and planning aspects known under the name of foodscapes are increasingly emerging at the local level, particularly in industrialized countries, where municipal governments are recasting themselves as food system innovators. Innovative forms of green urban architecture aimed at combining food, production, and design to produce food on a larger scale in and on buildings in urban areas are under study (Specht et al. 2014). Urban agriculture, whose return has an interesting parallel with the medieval city, with its inner gardens, should be developed in the future, supported by a different city-countryside relationship idea, closer to 'city and countryside', trough policies and education and a deeper analysis of environmental and energetic sustainability .

## Appendix. Summary of reviewed studies.

| Authors | Forms of Urban Agriculture | Location | Type of Impacts |
|---|---|---|---|
| Ackerman et al. 2014 | Urban agriculture | New York city (USA) | Economic, social and environmental benefits of UA and potential production |
| Adinolfi et al. 2013 | Urban green spaces, UGS | Granada (Spain) | Uses and functions of UGS |
| Al-Chalabi 2015 | Vertical farming (VF) | UK | Energy production and carbon footprint |
| Algert et al. 2014 | Community gardens | San Jose, California (USA) | Vegetable output and costs savings |
| Aubry et al. 2012 | Urban agriculture | Antananarivo (Madagascar) | Sustainability and multifunctionality |
| Badami and Ramankutti 2015 | Urban agriculture (vegetables) | High and low income countries (urban poor) | Food security and poverty alleviation |
| Barthel and Isendahl 2013 | Urban gardens | Maya cities and Costantinople | Food security and energy impacts |
| Bojacá and Schrevens 2010 | Peri-urban horticulture | Bogota, (Columbia) | Energy impacts of horticultural crops |
| Cavallo et al. 2016 | Farmers' markets, community supported agriculture | Rome (Italy) | Exploration of forms of UA |
| Chen 2012 | Civic agriculture and design of a civic agriculture community | South East USA | Civic agriculture community project at the neighbourhood scale |
| CoDyre et al. 2015 | Private gardens, community gardens | Guelph (Canada) | Productivity, Costs and potential of UA food production |
| Cohen and Reynolds 2014 | Urban agriculture | | Resource needs of UA |
| Corrigan 2011 | Community gardens | Baltimore, Maryland (USA) | Food security |
| Cretella and Buenger 2016 | Urban agriculture | Rotterdam (NL) | Economic and social goals in food policies |
| Dielman 2016 | Private gardens and community of farmers | Mexico city (Mexico) | Implementation of UA, sustainability and policy framework |
| Ferreira et al. 2013 | Urbang green infrastructure | Coimbra (Portugal) | Urban resilience |
| Fischer et al. 2013 | Urban green infrastructure | Berlin (Germany) | Capacity of conservation of grassland types |
| Grewal and Grewal 2012 | Urban agriculture | Cleveland (USA) | Potential level of food self-reliance |
| Guitart et al. 2012 | Community gardens | Developed and developing countries | Characteristics of CG , benefits and challenges |
| Guitart et al. 2014 | Community gardens | Brisbane and Gold Coast (Australia) | Health and agro-biodiversity |
| Haberman et al. 2014 | Urban agriculture (vegetable production) | Montréal (Canada) | Potential production of UA |
| Henke et al. 2015 | Peri-urban agriculture | Italy | Structural and economic characteristic of PUA |
| Henriques 2009 | Urban agriculture | Lisbon (Portugal) | Impacts of UA on building resilience |
| Huang and Drescher 2015 | Urban agriculture (crops and livestock products) | Two Canadian provinces | Potential differences between municipalities on planning UA |
| Lafontaine-Messier et al. 2016 | Urban Food trees | Villa El Salvador (Peru) | Financial benefits of introducing food trees in urban public green areas |
| Lehmanm 2014 | Green roof infrastructure | Sydney (Australia) | Urban heat mitigation |
| Liang et al. 2013 | Urban agriculture (livestock) | Beijing (China) | Estimation of GHG emissions from livestock sector |
| Lin et al. 2015 | Urban agriculture | | Biodiversity and eco-systems services |
| Longo 2016 | Urban farmers | Lafayette, California (USA) | Food security |
| Lovell 2010 | Urban agriculture | USA | Development, benefits, plannining and barriers of UA |
| Lupia and Pulighe 2015 | Private gardens | Rome (Italy) | Potential water demand |
| Marchetti et al. 2014 | | Italy | City-country relationship, urban sprawl, land use change and consumption |
| McCormack et al. 2010 | Farmers' market and community gardens | | Nutritional impacts |

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|---|---|---|---|
| Miccoli et al. 2016 | Urban agriculture | | Community esteem value |
| Middle et al. 2014 | Community gardens | Perth (Australia) | Ecosystems services |
| Mok et al. 2014 | Vertical farming, community farming, urban farmers, farmers' market, community supported agriculture | USA, Canada, UK, Australia, Japan. | Food self-sufficiency, environmental impacts (carbon footprint) |
| Monachie et al. 2012 | Urban and peri-urban agriculture | Freetwon (Sierra Leone) | Food security |
| Mullaney et al. 2015 | Urban food trees | | Environmental, economic and social benefits |
| Orsini et al. 2013 | Urban agriculture and horticulture | Developing countries | Pros and cons of UA |
| Pons et al. 2015 | Rooftop greenhouses | Barcelona (Spain) | Environmental impacts |
| Poulsen et al. 2015 | Urban agriculture | Low-income countries | Economic and social (e.g. food security) benefits |
| Pribadi and Pauleit 2015 | Peri-urban agriculture (PUA) | Jakarta Metropolitan Area (Indonesia) | Socio-economic benefit of PUA and agricultural types of PUA |
| Rowe 2011 | Green Roofs | | Mitigation pollution benefits |
| Sanyé-Mengual et al. 2012; 2015 | Rooftop greenhouses (tomatoes) | Barcelona (Spain) | Environmental Impacts (ADP, AP,EP, GWP, ODP, HTP, CED[30]) of life cycle tomatoes system and economic impacts |
| Torrigiani et al. 2012 | Rurality in urban fabric and urbanity in rural matrix | | Urban-rural interface and landscape identity |
| Vermeiren et al. 2013 | Subsistence farming, garden farming, commercial farming | Kampala (Uganda) | Potential spatial impacts of future urban growth to agricultural farmer's area |
| Warren et al. 2015 | Urban agriculture | | Food security, dietary diversity and nutrition security |
| Whittinghill et al. 2011 | Green roof (GR) technology in UA | | Benefits of GR and impacts on economic and food security of UA |
| Zasada 2011 | Peri-Urban Agriculture | | Multifunctionality of PUA, policy and planning for a multifunctional PUA |
| Zezza and Tasciotti 2010 | Urban agriculture | | Role of UA for urban households and relation between UA and food security |

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[30] ADP: Abiotic Depletion Potential, AP: Acidification Potential, EP: Eutrophication Potential, GWP: Global Warming Potential, ODP: Ozone layer Depletion Potential, http: Human Toxicity Potential, CED: Cumulative Energy Demand

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# CHAPTER 9– ENERGY AND MATERIAL EFFICIENCY IN BUILDINGS

Circular economy as a new model of economic development promotes the maximum reuse/recycling of materials, goods and components in order to decrease waste generation to the largest possible extent. Its aims to innovate the entire chain of production, consumption, distribution and recovery of materials and energy according to a cradle to cradle vision. As pointed out in the introduction to this deliverable, material efficiency (i.e. recovering still useful materials) helps saving energy over the entire production chain in so translating into a different way to achieve energy efficiency.
Within such a vision, in the last two decades a growing literature addressed the environmental and economic impacts of construction and demolition sectors with special focus on the production and management of its waste materials. This chapter first focuses on a specific survey abut energy use and energy efficiency potential in a building of Parthenope University (Chapter 9.a); then, it deals with the extent of achievable material and energy efficiency by means of material recovery in buildings. We review the recent literature to explore to what extent the adoption of circular economy methods in this sector is beneficial to the economic and environmental systems. The investigated environmental impacts have been mainly quantified by means of the Life Cycle Assessment approach, under the adoption of different boundaries of analysis. Recycled and reused products are shown to provide environmental and economic benefits. In order to properly account for the several factors that affect the value of benefits, the adoption of a comprehensive accounting of output flows becomes a crucial issue. Different type of barriers (economic, legislative, political, technological, and informative) as well as solutions and success factors for implementing an effective management of construction and demolition waste within a circular framework are evidenced in the reviewed literature.

The present Chapter is organized as:

CHAPTER 9.a Energy Efficiency in Universities. The case study of Palazzo Pacanowsky, Napoli, Italy

CHAPTER 9.b – Material Efficiency in Buildings and related energy savings. Exploring environmental and economic costs and benefits of a circular economy approach to construction and demolition materials.

## CHAPTER 9.a Energy Efficiency in Universities. The case study of Palazzo Pacanowsky, Napoli, Italy

*Introduction*

Palazzo Pacanowsky today consists of 25 classrooms for about 2,300 seats, 149 offices, computer rooms, meeting rooms, reading rooms, a canteen, a bar, a parking garage with a capacity of about 170 cars, spread over 35,000 m2.

*Analysis of consumption*

In order to identify corrective actions for the reduction of electricity supply costs of this building, it was necessary, as a first step, to make a detailed analysis of electricity consumption. Below we report the results of this analysis for the years 2012 and 2013 (it should be noted, in this regard, that the structure became operational in 2012) through the detailed examination of invoices relating to the supply of electricity. From the bills, monthly electricity consumption was detected for the three time periods F1, F2 and F3. The consumption, for the year 2012, is given in table 1. In particular, the table shows the active monthly energy values consumed in the absence and in the presence of network losses, fixed to 4.7%.

**Table 1 Electrical consumption year 2012**

| | Active energy consumed in the three periods with no losses [kWh] | | | | Active energy consumed in the three periods with losses [kWh] | | | |
|---|---|---|---|---|---|---|---|---|
| **Month** | **F1** | **F2** | **F3** | **total** | **F1** | **F2** | **F3** | **total** |
| jan-12 | Not available | | | | Not available | | | |
| feb-12 | 117887 | 21539 | 34563 | 173989 | 123428 | 22551 | 36187 | 182166 |
| mar-12 | 140324 | 25933 | 36003 | 202260 | 146919 | 27152 | 37695 | 211766 |
| apr-12 | 110957 | 30592 | 34639 | 176188 | 116172 | 32030 | 36267 | 184469 |
| may-12 | 33555 | 14193 | 29166 | 76914 | 35132 | 14860 | 30537 | 80529 |
| jun-12 | 44506 | 18996 | 31805 | 95307 | 46598 | 19889 | 33300 | 99786 |
| jul-12 | 101632 | 22682 | 33003 | 157317 | 106409 | 23748 | 34554 | 164711 |
| aug-12 | 139933 | 23863 | 34244 | 198040 | 146510 | 24985 | 35853 | 207348 |
| sep-12 | 15088 | 10901 | 20562 | 46551 | 15797 | 11413 | 21528 | 48739 |
| oct-12 | 98586 | 18323 | 26555 | 143464 | 103220 | 19184 | 27803 | 150207 |
| nov-12 | 134663 | 21672 | 27445 | 183780 | 140992 | 22691 | 28735 | 192418 |
| dic-12 | 43855 | 14827 | 25346 | 84028 | 45916 | 15524 | 26537 | 87977 |
| **total** | **980986** | **223521** | **333331** | **1537838** | **1027092** | **234026** | **348998** | **1610116** |

Despite the presence of a system of automated power factor correction, from billing documents it has been detected the monthly payment of a penalty relating to an excessive consumption of reactive energy. Table 2 shows the values of the penalties for the consumption of reactive power paid for the year 2012.

**Table 2 – Penalties for reactive power consumption year 2012**

| Month | Penalty [€] |
|---|---|
| January | Not available |
| February | 510,01 |
| March | 502,24 |
| April | 521,64 |
| May | 550,09 |
| June | 643,47 |
| July | 762,28 |
| August | 945,45 |
| September | 473,71 |
| October | 327,34 |
| November | 609,83 |
| Dicember | Not available |

It was therefore decided to test the correct operation of power factor correction; from the test, a system failure showed up and, therefore, it was decided to restore normal operation. This intervention brought the penalties down to zero, as from July 2013.
Consumption for the year 2013 is shown in Table 3. The table shows the values of active energy consumed in the absence and in the presence of network losses, set at 4.0%.

**Table 3 Electrical consumption jan-jun 2013**

| | Active energy consumed in the three periods with no losses [kWh] | | | | Active energy consumed in the three periods with losses [kWh] | | | |
|---|---|---|---|---|---|---|---|---|
| **Month** | **F1** | **F2** | **F3** | **total** | **F1** | **F2** | **F3** | **total** |
| jan-13 | 137894 | 28243 | 36769 | 202906 | 143410 | 29373 | 38240 | 211023 |
| feb-13 | 140398 | 28019 | 33224 | 201641 | 146014 | 29140 | 34553 | 209707 |
| mar-13 | 132703 | 27142 | 37649 | 197494 | 138011 | 28228 | 39155 | 205394 |
| apr-13 | 42298 | 15610 | 29020 | 86928 | 43990 | 16234 | 30181 | 90405 |
| may-13 | 57642 | 18460 | 28958 | 105060 | 59948 | 19198 | 30116 | 109262 |
| jun-13 | 119069 | 24301 | 33046 | 176416 | 123832 | 25273 | 34368 | 183473 |
| jul-13 | 164548 | 39985 | 52088 | 256621 | 171130 | 41584 | 54172 | 266886 |
| aug-13 | 96350 | 23413 | 30500 | 150263 | 100204 | 24350 | 31720 | 156274 |
| sep-13 | 144494 | 29613 | 38825 | 212932 | 150274 | 30798 | 40378 | 221449 |
| oct-13 | 168501 | 38492 | 38104 | 245097 | 175241 | 40032 | 39628 | 254901 |
| nov-13 | 113770 | 32744 | 33771 | 180285 | 118321 | 34054 | 35122 | 187496 |
| dic-13 | 127568 | 33357 | 33251 | 194176 | 132671 | 34691 | 34581 | 201943 |
| **total** | **1445235** | **339379** | **425205** | **2209819** | **1503046** | **352955** | **442214** | **2298212** |

The total energy consumption in the year 2013, including network losses, was about 2300 MWh (an increase compared to 2012, in February-December period, of about 30%).

*Diagrams of daily load*

With reference to the site in the study, the hourly consumptions relative to a summer and a winter day day are reported (Figures 1 and 2 for the year 2012, and Figures 3 and 4 for the year 2013).
The load diagrams, representative of consumption in the two seasons, showed a variability in the 24 hours with load peaks in the period 7:00 to 17:00 due to the satisfaction of the thermal and refrigeration load during the opening hours of the structure.

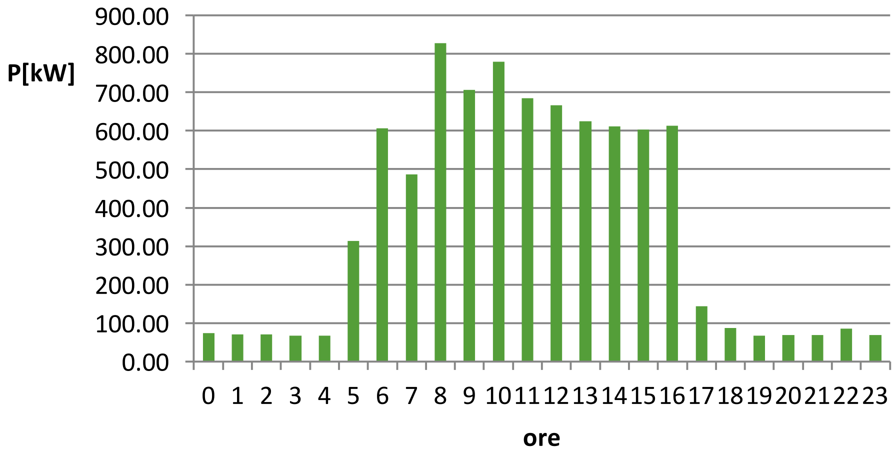


**Figure 1 Time diagram of a winter day (03.12.2012)**

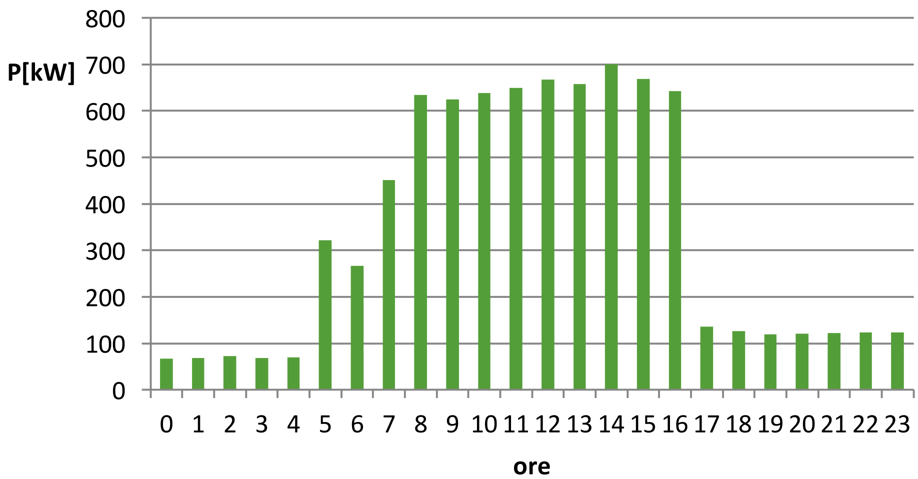


**Figure 2 Time diagram of a summer day *(02.07.2012)***

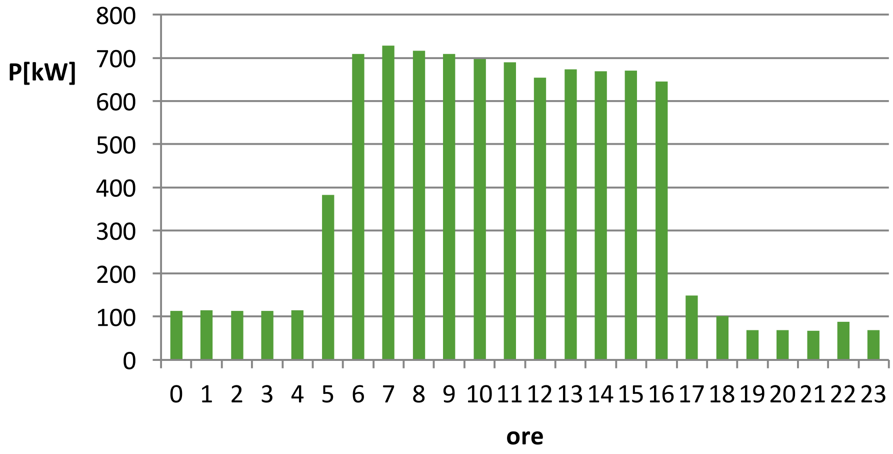


**Figure 3 Time diagram of a winter day (14.01.2013)**

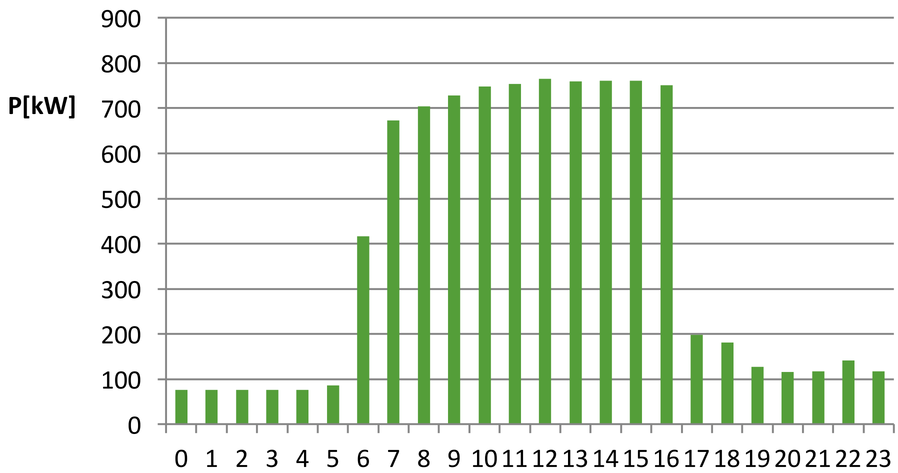


**Figure 4 Time diagram of a summer day (02.07.2013)**

From the load charts we notice that there is no substantial difference between summer and winter consumption. This is related to the fact that in the hours of opening of the facility, as already mentioned, consumption is mainly due to the air conditioning that heats in winter and cools in summer.

In recent years, the energy efficiency of buildings has assumed increasing attention at local and national level. Given the importance of "sustainable building" and the need to reduce the final energy consumption, laws and decrees were issued, both at European and national level, addressing energy efficiency linked to buildings.

The certificate of Energy Certification is defined in the Directive as the document that "includes reference data, such as current values according to the law and the reference values, which allow consumers to compare and assess its energy performance" (Art .7, paragraph 2). Directive 2010/31/EU (known as EPBD recast), implemented in Italy with Decree Law June 4, 2013, 63, in Art. 12 par.1, point b, reiterated this concept by requiring buildings with a useful floor area totaling over 500 m2, occupied by a public authority and frequently visited by the public, to adopt Attestation Energy Performance.

*Energy saving measures*

** Possible measures to reduce heat consumption*

In order to improve the energy performance of the building Pacanowski, the Energy Commission has proposed the following energy saving measures:

- reducing ventilation rates in the environments
- installation of heat recovery at AHU (Air Handling Unit);
- Energy saving on the user side.

One type of intervention analyzed is related to the installation of heat recovery at AHU of the building. A heat exchanger pre-heats or pre-cools, depending on the air conditioning season, the fresh air by recovering energy from the exhaust air. The recovery of heat can be of two types: sensible and latent. In the first case, there is a transfer of the enthalpy contents of one of two fluids in order to pre-treat the air. The latent recovery is obtained, instead, by condensing the water vapor contained in the air to be treated. In summer, for example, the outside air is characterized by high relative humidity values and the dehumidification of the fluid, before being displaced in the environment, involves the loss of an energy content, known as latent heat of vaporization. In order to carry out this drying, the treated air coming from the air-conditioned, cold and dried, before being expelled is channeled in an exchanger by absorbing this heat and operating a pre-dehumidification of new air. Obviously, in the case where there is a latent recovery, it is also sensitive.

In the market, several types of recovery units are available:

Static heat recovery plate;

Rotary regenerators;

Regenerators with pump batteries (run around);

Recovery of heat pipes (heat pipe).

In the specific case it is proposed the installation at the AHU of a high-efficiency rotary heat recovery characterized by winter and summer efficiencies of 80% minimizing the expenditure of energy for ventilation. Since the employment rate of the classrooms and offices is not always continuous and constant throughout the day and in different months of the year, we could plan the early shutdown of some AHU, for example reorganizing the educational activities so that course readings end before 17:00.

Shutdown of AHU implies the curtailment of the load of the heat pump because it interrupts the flow of hot water from the heating plant to the AHU batteries.

** Possible measures to reduce electricity consumption*

The following table shows some of the actions that could be put in place to contain power consumption of the structure.

**Table 4 – Electricity saving measures**

| TYPE OF CONSUMPTION | INTERVENTION |
|---|---|
| Air conditioning | • Carefully choose the set point temperature to ensure in the environment, disabling, eventually, the use of the current thermostats<br>• Delaying the time of turning ON the air-conditioning<br>• Anticipate the shutdown time of the air conditioning |
| Lighting | • Replacing bulbs currently in use with more energy-efficient lamps<br>• Switching on and off of the studies using occupancy sensors<br>• Switching on and off in the bathrooms via presence sensors<br>• Installation of automatic devices to control lighting (use of flow regulators in daylight-dependent on a structure like that of Via Parisi, with coverage mainly through glass, could lead to major savings in fuel consumption for lighting)<br>• Partitioned lighting in the hallways during less busy hours |
| Stand-by | • To sensitize staff to the shutdown of electrical equipment.<br>• Installation of smart devices to switch off devices in stand-by |
| Reactive power | • As noted in the previous report, it is necessary to verify the correct operation of the reactive compensation system to avoid the payment of penalties. |
| Losses in transformers | • Taking account of the existing power absorption, in order to stem losses and, consequently, their costs, the service should be maintained in only three of the seven transformers installed in the cabin. |

*Conclusions*

The report showed that the analyzed structure is particularly energy-consuming. The saving interventions analyzed have resulted in energy savings are not supported by economic savings. In some cases, such as the relevant assistance to installation of heat recovery, the increase in electricity consumption related to the exercise of the latter has not been offset by the reduction of electricity consumption of the heat pump related to the decrease of the load heat user. The assumptions concerning the anticipated shutdown of some AHU have instead resulted in a cost savings of about 30,000 Euros/year. This analysis therefore shows the need to make a careful monitoring of the structure in terms of employment of the classrooms in order to optimize plant operations.

**CHAPTER 9.b – Material Efficiency in Buildings. Exploring energy, environmental and economic costs and benefits of a circular economy approach to construction and demolition materials.**

*Introduction*

The Circular Economy (CE) is becoming a new frontier for worldwide economic systems, aiming to replace the current linear economic model. CE promotes a model that is restorative by intention and design (Ellen Mac Arthur Foundation 2012) as its main idea is to maximize the reusability of products and components rather than discarding them at the end of their useful life. As in natural ecosystems, processes and activities are designed to be waste free (Ghisellini et al. 2016; Park and Chertow 2014; Su et al. 2013; Geng et al. 2010; Yuan et al. 2006). Waste of post-consumption phases are part of a continuous material loop that should not be blocked as in the linear model of economy (Altamura 2013).

The reclaim and recovery of materials from waste requires energy, machinery and human labor, in other words requires investments. Nevertheless, the global economy can no longer afford to throw away anything (Altamura 2013; Lynch 1992) because of the environmental challenges, the shortage of strategic resources as well as of spaces for landfill purposes (Knoeri et al. 2013; Ortiz et al. 2010). CE looks for reducing the use of environment as a sink and, even more important, looks for innovating the entire chain of production, consumption, distribution and recovery of products according to a cradle to cradle vision (Genovese et al. 2015; Chiaroni and Chiesa 2014). Circular economy should necessarily rely on renewable energies paving the way to fossil fuels' savings and future phase out (Preston 2012).

In the last two decades an increasing trend of research has been devoted to the evaluation of the sustainability of construction and demolition sector, that has a huge impact on environment and generates a large amount of waste (Duan et al. 2014; Proietti et al. 2013; Yuan et al. 2011; Lu and Yuan 2010; Da Rocha and Sattler 2009; Brown and Buranakarn 2003). Worldwide construction and demolition waste, (C&D waste), are a serious environmental problem accounting for a relevant share of total waste produced (Brasileiro and Matos 2015; Diyamandoglu and Fortuna 2105; Martinez et al. 2015; Rodriguez et al. 2015; Marzouk and Azab 2014; Knoeri et al. 2013).

Recycling and/or recovery of C&D waste is being carried out in many countries in Europe (European Commission 2016; Dahlbo et al. 2015; La Marca et al. 2010; Ortiz et al. 2010) and worldwide (Zhu and Chertow 2016; Brasileiro and Matos 2015; Diyamandoglu and Fortuna 2015; Knoeri et al. 2013; Da Rocha and Sattler 2009; Nunes et al. 2009; Tam 2009; Bianchi 2008). The EU Waste Framework Directive (2008/98/EC) prioritizes reuse over destructive recycling in its waste hierarchy and states that by the year 2020 a minimum of 70% (by weight) of non-hazardous construction and demolition waste should be reused/recycled or undergo other types of material recovery (Huuhka et al. 2015; Rodriguez et al. 2015).

The main goal of this study, by reviewing the recent literature, is understanding to what extent it is environmentally and economically feasible and desirable to apply a circular economy approach to the construction and demolition sector.

The chapter is structured as follows. First we briefly introduce the method to dig the selected literature. Then, we analyze the implications of the adoption of a circular approach in construction and demolition sector, as they emerge from the reviewed literature. Next, we deepen on the main features of construction and demolition waste and demolition techniques. The Results section stresses the main findings from selected literature. Our efforts aim to point out how the circular economy approach has been implemented. Finally, the last section discusses perspectives and needs for CE in the C&D sector and main conclusions.

*Materials and Methods*

Selected recent articles have been identified after conducting a search on all databases of Web of Science[31]. We limited our attention to articles published in the last six years and dealt with the analysis of environmental and economic impacts of recycling and/or reusing of C&D waste. We entered several keywords and screened titles, abstracts and contents of the articles found through this search. **Table 1** show the selected articles listed in alphabetical order with regard to the author/s. Information about the object of analysis (waste, material products or entire buildings), type of solutions, country/region under study as well as performed method are also included in the Table. From Table 1 life cycle assessment emerges as the most used method of analysis.

**Table 1.** Selected articles listed in alphabetical order with regard to Author/s' last name

| Author/s' | Object of Analysis | City/Country under study | Method of analysis |
|---|---|---|---|
| Ajayi et al. 2015 | C&D waste management strategies | United Kingdom | Focus group |
| Ardente et al. 2009 | Building | Southern Italy | Full life cycle assessment |
| Behera et al. 2014 | Recycled aggregates and recycled concrete aggregates | India and Worldwide | Literature review |
| Blengini and Garbarino 2012 | Recycled aggregates | Turin (Italy) | Life cycle assessment |
| Blengini 2009 | Building | Turin (Italy) | Full life cycle assessment |
| Coelho and De Brito, 2012a | Recycling plant | Lisbon (Portugal) | Economic analysis |
| Coelho and De Brito, 2013b | Recycling plant | Lisbon (Portugal) | Economic analysis |
| Coelho and De Brito, 2012 | Building | Portugal | Life cycle assessment |
| Coelho and De Brito, 2011 | End-of-life options | Lisbon (Portugal) | Economic analysis |

31 https://apps.webofknowledge.com/UA_GeneralSearch_input.do?product=UA&search_mode=GeneralSearch&SID=T2Cisx9srHsTR3ZNl3M&preferencesSaved=

| | | | |
|---|---|---|---|
| Cuellar-Franca and Azapagic 2012 | Buildings | United Kingdom | Full life cycle assessment |
| Dahlbo et al. 2015 | C&D waste system | Finland | Life Cycle Assessment, Material Flow Accounting, Environmental Life Cycle Costing |
| Da Rocha and Sattler 2009 | Deconstruction waste | Brazil | Interviews and literature review |
| Ding et al. 2016 | Natural and recycled concrete aggregates | China | Life cycle assessment |
| Diyamandoglu and Fortuna 2015 | Deconstruction waste | USA | Streamlined life cycle assessment |
| Duan et al. 2014 | End-of-life options for C&D waste | China | Literature review |
| Faleschini et al. 2016 | Recycled concrete aggregates | Italy | Life cycle assessment |
| Ferreira et al. 2015 | Building | Lisbon (Portugal) | Life cycle assessment |
| Gangolells et al. 2014 | C&D Waste | Spain | Questionnaire survey |
| Gaspar and Santos 2015 | Building | (Lisbon) Portugal | Energy analysis |
| | | | |
| Hossain et al. 2016 | Natural and recycled aggregates | Hong Kong (China) | Life cycle assessment |
| Knoeri et al. 2013 | Natural and recycled concrete aggregates | Switzerland | Life cycle assessment |
| Kucukvar et al. 2014 | End-of-life options for C&D waste | USA | Hybrid life cycle Assessment |
| La Marca 2010 | Demolition waste | Rome (Italy) | Life cycle assessment |
| Lu and Yuan 2010 | C&D waste management | Shenzhen (China) | Questionnaire survey and interviews |
| Lawania et al. 2015 | Building | Perth (Australia) | Streamlined life cycle Assessment |
| Marinković et al. 2010 | Natural and recycled concrete aggregates | Serbia | Life cycle assessment |
| Martinez et al. 2013 | End-of-life options for C&D waste | Spain | Life cycle assessment |
| Marzouk and Azab 2014 | End-of-life options for C&D waste | Egypt | System Dynamics Model |
| Mercante et al. 2012 | C&D waste management system | Spain | Life cycle assessment |
| Ng & Chau 2015 | End-of-life options for C&D waste | China | Life cycle energy analysis |
| Nunes et al. 2009 | C&D waste management system | Brazil | Case study |
| Ortiz et al. 2010 | Construction waste | Catalonia (Spain) | Life cycle assessment |
| Oydele et al. 2014 | Construction waste | United Kingdom | Questionnaire survey |
| Proietti et al. 2013 | Building | Perugia (Italy) | Full life cycle assessment |
| Serres et al. 2016 | Natural and recycled concrete aggregates | France | Life cycle assessment |
| Silva et al. 2014 | Recycle aggregates | Worldwide | Review |
| Srour et al. 2013 | Demolition waste | Beirut (Lebanon) | Financial analysis based on literature review and survey |
| Tam 2009 | Recycled concrete aggregates | Australia and Japan | Questionnaire survey |
| Tosic et al. 2015 | Natural and recycled concrete aggregates | Serbia | LCA, Cost analysis, Multi-criteria Optimization model |

| | | | |
|---|---|---|---|
| Turk et al. 2015 | Natural and recycled concrete aggregates | | Life cycle assessment |
| Yuan et al. 2011 | End-of-life options for C&D waste | Shanghai (China) | Emergy Analysis |
| Vitale et al. 2016 | End-of-life options for C&D waste | Italy | Life cycle assessment |

*Circular economy approach in construction and demolition sector*

The adoption of a circular model in construction and demolition implies a great change of perspective and methods in its current practice. Buildings and infrastructure are designed to maximize lifespan and dismantling, offer space for changing functions as well as modify aesthetic or technological elements (ABN AMRO 2014).

The optimization and re-using of existing supply of buildings and infrastructures and the design of buildings according to the principles of a circular approach are relevant strategies for the transition (Osmani et al. 2008). Circular design aims to identify new end-of-life scenarios for construction and demolition waste materials, according to a closing-the-loop approach that eliminates the concept itself of waste in the short and long run (Altamura 2013). Specifically circular design means "*designing a building (or infrastructure) in such a way that is built out of components or parts that can be disassembled – e.g facades, windows, doors, floors and structural elements. The necessary resources for this must be recyclable in a high-value way. When you disconnect the exterior, architectural characteristics from the structure, this increases the adaptability of the building"* (ABN AMRO 2014).

To cope with the environmental problems related to the disassembly of materials the entire material stream over the life cycle of a building should be taken into account starting from the pre-design phase till the demolition, reuse and recycling (**Figure 1**). Reuse and recycling contribute to closing the cycle and to reintroducing materials in the building construction industry cycle again. The reuse implies the use of the products in its original form with minimum operations of recovery. The recycle, instead, lead to the recovery of materials in a product to be reprocessed and transformed in materials of lower quality and performances (Altamura 2013). In the waste hierarchy of EU and USA (Huuhka et al. 2015; Rodriguez et al. 2015; Park and Chertow 2014), reuse is a better option than recycling as it contributes to reduce the quantity of waste disposed of in landfills, generate higher energy and emissions savings and employment opportunities in construction industry and management of waste (Altamura 2013).

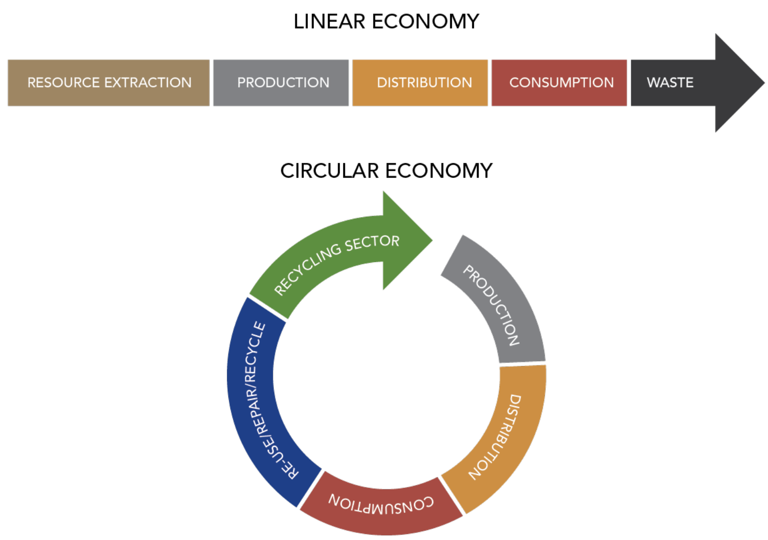


Figure 1.

The focus on closing the loop also evidences the importance of analysis and management of inputs and outputs of the whole life cycle of a building. The goal is to design buildings with lower input demand and with parts that can be re-assembled in the future without risks for the environment and human health (Altamura 2013).

*Overview of Construction and Demolition waste characteristics*

C&D waste consist of different types of materials in variable amounts, depending on several factors such as their sources (residential, commercial, industrial buildings, roads, bridges, etc.), size (low-rise, high-rise), the type and method of activity that is carried out (e.g. construction, renovation, repair, demolition/deconstruction) and the location of the development (Diyamandoglu and Fortuna 2015; Silva et al. 2014; La Marca 2010; Zhao et al. 2010). In USA, the use of wood in building construction is dominant (from one forth to two thirds). In European countries, C&D waste mainly consist of bricks and concrete (80-83%), the rest (17-20%) are packing and structure support materials (such as plastics, wood, metal, paper and cardboard) as well as overburden, namely material coming from excavation sites (clay and rocks, asphalt) (Mercante et al. 2012; La Marca 2010). Three main types of C&D materials can be identified: crushed concrete, crushed masonry, and mixed demolition debris. After crushing and beneficiation process[32] in certified recycling plants, the resulting aggregates can be classified in four categories: recycled concrete aggregates, recycled masonry aggregates, mixed recycled aggregates and construction and demolition recycled aggregates (Behera et al. 2014; Silva et al. 2014). Recycled aggregates may undergo several utilizations depending on their quality. Low quality recycled aggregates are used for environmental filling and rehabilitation of depleted

[32] Beneficiation is the process applied to aggregate production for the selective removal of contaminants in the aggregate. (Alexander and Mindess) 2010.

quarries and landfill sites; medium quality aggregates can be used for some parts of road, airport and harbor construction, higher quality aggregates are used in concrete and mortar production and road construction (Silva et al. 2014; Blenghini and Garbarino 2010).

With regard to recycled aggregates, Behera et al. (2014) and Silva et al. (2014) provided an extensive overview of production and use of recycled aggregates (RA) and recycled concrete aggregates (RCA) reviewing their properties, composition, techniques for improving the performances and the durability. Behera et al. (2014) found that mechanical and durability performance of RCA are lower than conventional concrete even if the use of Recycled Aggregate (RA) for structural applications is increasing. Silva et al. (2014) note that the characterization of quality, composition and properties of an RA should be defined exactly for their use in concrete production to improve its classification, understanding of the material, potential performance, certification and confidence from stakeholder's. If an RA is "*properly processed and classified it may be considered as another type of normal aggregate, fit for use in construction as per national and international specifications*" (Silva et al. 2014).

*Demolition and deconstruction techniques*

The type of demolition techniques largely influence the quality of C&D waste (Bianchi 2008). The secondary materials obtained from homogeneous C&D waste are of higher quality than secondary materials derived from heterogeneous C&D waste (Nunes et al. 2009; Bianchi 2008). The separation into homogeneous fractions should be carefully adopted in the demolition process to favor the reusability/recyclability of the largest possible fraction of C&D waste. This practice is not always performed (Duan et al. 2014; Nunes et al. 2009) so that most often the recycled materials do not have homogenous physical or chemical characteristics. Unfortunately, this prevents their use in higher quality products as concrete structures (Nunes et al. 2009).

Conventional demolition, is a process performed with mechanical equipment without much attention to separation of components. It is a quick and less expensive way for clearing sites of their buildings, but on the other hand it creates a substantial amount of amorphous materials to be treated and disposed of (Duan et al. 2014; Da Rocha and Sattler 2009). Instead, deconstruction is considered a better and viable alternative from an environmental and socio-economical point of view (Diyamandoglu and Fortuna 2015; Silva et al. 2014; Proietti et al. 2013; Coehlo and Brito 2012; Da Rocha and Sattler 2009; Bianchi 2008). It implies the sequencing of demolition activities to obtain the separation and sorting of valuable building materials as bricks, windows, tiles (Da Rocha and Sattler 2009; Bianchi 2008). Generally it is classified into two categories: deconstruction of structural elements and deconstruction of non-structural elements (also known as soft-stripping). The adoption of deconstruction is also needed for obtaining materials with reduced level of contaminants and higher values of recycled aggregate (Silva et al. 2014).

A mixture of the two techniques, e.g. removal of non-structural elements for recycling, followed by traditional demolition of all the other materials, does not lead to significant environmental benefits as transportation distances to recycling plants are mainly travelled by diesel trucks (Coehlo and Brito 2012).

*Modeling impacts of circular economy for C&D waste*

Industrial ecology with its eco-systemic perspective and well-known tools as Life Cycle Assessment (LCA) and Material Flow Accounting (MFA) is an essential theoretical and analytical framework for developing and implementing a circular economy (Birat 2015; Dahlbo et al. 2015; Deutz and Ioppolo 2015). LCA needs to be modeled properly for the purpose of accounting the environmental benefits arising from recycling or reuse of C&D waste materials (Birat 2015; Thomas and Birat 2013) and integrated at the macro scale by MFA and other tools such as scenario analysis, backcasting and input-output analysis (Birat 2015; Dahlbo et al. 2015). The time dimension of CE is a crucial aspects so that dynamic MFA and LCA are suggested as the best models for incorporating time aspects (Birat 2015). Brown and Buranakarn (2003) also propose the integration of LCA within Emergy Analysis' framework to overcome the drawbacks of LCA. The latter provides as results rankings and indicators in mixed units (e.g. $CO_2$ production, energy consumed, human capital required etc.) rendering difficult the comparison of environmental performances between products or services. Emergy-life-cycle-assessment methodology accounts for materials, energy, and human services, within the same quantitative framework and provides further quantitative recycling indices (such as recycling benefit ratio, recycling yield ratio, landfill to recycle ratio) for comparison of materials from C&D waste within a LCA (Brown and Buranakarn 2003).

Several authors in this review analyzed the environmental impacts, by carrying out life cycle assessments (LCA) of recycled products from C&D waste (e.g. recycled concrete aggregates) as well as of end-of-life management options for C&D waste (Diyamandoglu and Fortuna 2015; Kucukvar et al. 2014; Martinez et al. 2013; Yuan et al. 2011; La Marca 2010; Ortiz et al. 2010). Other studies analyze the environmental impacts of using by-products and recyclates from C&D waste in building construction (Lawania et al. 2015; Coelho and Brito 2012) by performing a simplified and quicker form of LCA, the so-called streamlined life cycle assessment (Todd et al. 1999; Curran 1996). A few evaluated the full life cycle of a building involving the use of recycled materials from C&D waste (Proietti et al. 2013; Cuellar-Franca and Azapagic 2012). Three studies combined the analysis of environmental and socio-economic impacts of C&D waste management (Dahlbo et al. 2015; Tosic et al. 2015; Marzouk and Azab 2014). The adoption of such a framework provides with the opportunity of evaluating and improving a system on the basis of a multi-criteria approach (Dahlbo et al. 2015). Finally, some studies analyzed economic impacts of investments in recycling plants for the treatment of C&D waste, by carrying out a Financial Analysis and a Cost-benefit Analysis (Srour et al. 2013; Zhao et al. 2010). Table 2 lists the above LCA studies providing details about the life cycle impact assessment methods used and the evaluated impact categories.

**Table 2.** Life Cycle Impact Assessment (LCIA) results for the most common impact categories analysed in the reviewed studies (total life cycle impacts), data per m$^2$ and per year.

| Authors | Boundaries of analysis | GER (MJ) | GWP (kg $CO_2$ eq.) | ODP (kg $CFC_{11}$ eq.) | AP (kg SO2 eq.) | EP (kg $PO_4^{3-}$ eq) | POCP (kg $C_2H_4$) |
|---|---|---|---|---|---|---|---|
| Blengini 2009 | Cradle to grave | 998. 60 | 66.80 | 0.00003 | | | 0.00094 |
| Cuellar-Franca and Azapagic 2012 | Cradle to grave | | 3500 | | | | |
| Proietti et al. 2013** | Cradle to cradle | 4.87 | 5.12 | | -1.37E-03 | 1.75E-02 | 0.00398 |
| Ardente et al. 2009 | Cradle to grave | 860.00 | 327.90 | 0.04 | 1.34 | 137 | 60 |
| Coehlo and De Brito 2012* | Material stage and end-of-life phase | | 65.30 | | 0.60 | 0.09 | 0.10 |
| Lawania et al. 2015*** | Material stage and use stage | | 1680.00 | | | | |

*The data are referred to the scenario 5 involving the highest percentage of recycling and reuse of components (96.3%). Only building material stage and end-of-life are considered in this study.

** $GWP_{100}$ global warming potential, 100-year time horizon.

***End-of-life is excluded. In building construction are considered the use of recycled materials such as recycled crushed aggregate.

## *Results*

### *Environmental impacts of a building that reuses C&D waste*

The life cycle of a building includes three phases: pre-utilization (from materials extraction and production and building), utilization phase (occupation and ordinary maintenance) and end-of-life phase (from conventional demolition or selective demolition to the waste treatment consisting of reuse/recycling processes and/or landfilling of materials). Proietti et al. (2013) analyzed the environmental impacts of a passive house in central Italy from pre-utilization up to end-of-life assuming 100% recycling of C&D waste. They found that the inclusion of specific materials (steel structure and the absence of brick walls), allowing the adoption of a selective deconstruction, lead to a reduction of the energy impacts in the deconstruction processes at the end-of-life phase. The related environmental benefits are estimated around 20%, due to avoided impacts in the Gross Energy Requirement (GER) and Non-Renewable Energy demand (NRE). The comparison of recycling/reusing and landfilling scenarios, highlights that the choice of recycling/reusing rather than landfilling reduces the contribution to GWP (-87%) and GER (-90%) over the whole life cycle. The study also shows that renewable electricity from a solar PV (photovoltaic) plant installed on the roof reduced significantly the contribution to GWP and GER in the use's phase.

Cuellar-Franca and Azapagic (2012) evaluated the environmental impacts[33] of three types of buildings in United Kingdom: detached, semi-detached and terraced. They found that most of the contribution to GWP comes from use (90%) and construction stage (9%) for the three types of houses. The GWP results suggest the need for construction designs and materials capable to decrease the energy use during the use phase. The Authors also evidence a reduction of all impact categories due to reusing the bricks and recycling the aggregates at the end-of-life. The contribution to GWP of the whole life cycle reduces by 3% (detached and semi-detached) and 2% (terraced house) and by about 28% the impact of construction stage to total GWP.

Lawania et al. (2015) analyze and compare Greenhouse Gas (GHG) emissions and embodied energy consumption of a residential Australian house up to utilization stage. They also estimate the environmental benefits generated by the use of cleaner production strategies implying the use of alternative wall systems compared to clay bricks wall system as well as the substitution of constituents of concrete with by-products and recyclates. Concrete mainly consists of three products such as cement, aggregates and sand. These constituents of conventional cement concrete have been partially substituted by a combination of by-products including, fly ash (FA), ground granulated blast furnace slag (GGBFS), recycled crushed aggregates (RCA) and manufactured sand (MS). Moreover, for sandwich walls the polystyrene core has been replaced by polyethylene terephthalate (PET) foam manufactured from post consumed PET bottles. The results evidence reduction of GHG emissions and embodied energy consumption by 8.10% and 8.89% respectively due to the adoption of cleaner production strategies.

Coehlo and Brito (2012) compare the environmental impacts of generic buildings considering different scenarios of materials stage and end-of-life stages. The Authors point out a relevant reduction of the impacts in the materials stage, by shifting to scenarios with higher fraction of recycling/reusing of waste materials (more than 95% of the materials are recycled/reused) and their use into new constructions. GWP decreases by 77%, Heavy metal by 88% and Summer Smog by 81%. In the whole life cycle the reductions to GWP (-6%) and AP (-7%) are lower compared to the decrease to Heavy metal (-40%). They conclude by noting the need for policy making to enhance recycling and reintroduction of materials into the construction industry cycle rather than stimulate materials' reuse as it is difficult to obtain high quantity of well-maintained salvaged materials.

*Environmental impacts of products derived from C&D waste*

Reused and recycled products from C&D waste, being a relevant source of materials, are necessary in improving self-sufficiency in construction sector. They

[33] GWP: Global warming potential; AP: Acidification potential; ADP: Abiotic depletion potential; EP: Eutrophication potential; ODP: Ozone layer depletion potential, HTP: Human toxicity potential; TETP: Terrestrial ecotoxicity potential; FAETP: Freshwater aquatic ecotoxicity potential; MAETP: Marine aquatic ecotoxicity potential; POCP: Photochemical ozone creation potential

should be included in a philosophical framework aimed to increase the weight of building maintenance and retrofitting compared to the current trend towards new constructions (Coehlo 2016). Several selected studies carried out LCAs for the analysis of environmental profiles of products derived from recycled materials.

Guignot et al. (2015) compared the LCA impacts of processing of 1 kg of concrete waste from C&D operations in the current recycling scheme (and use in road construction) versus an alternative recycling scheme. The latter implies the adoption of a new technology for the processing of gravel based on electrical fragmentation. In this way recycled concrete aggregate can be used for high-quality structural concrete applications and recycled cement paste as a substitute to natural minerals in clinker kilns. Three scenarios are considered with different transport distances and modes of transport of waste. The results point out the potential environmental benefits of the alternative recycling schemes, in all the assessed impact categories.

Marinković et al. (2010) evaluated the environmental impacts of producing and transporting 1 $m^3$ of natural concrete aggregate (NCA) and recycled concrete aggregate (RCA) in Serbia. The system's boundaries include production and transport of aggregate and cement, as well as production and transport of concrete from concrete plant to the construction site (construction, service and demolition phases are excluded). The results of first scenario show that total environmental impacts for each category are slightly higher for RCA than for NCA even assuming lower transport distance for RCA than NCA. Of course, in the second scenario, with equal transport distances, the environmental impacts of RCA are much higher than NCA. Knoeri et al. (2013) analyzed the life cycle impacts of 12 recycled concrete (RC) mixtures with two different cement types and compared recycled concrete mixtures with conventional concretes (CC) mixtures for three structural applications in the Switzerland context. They also investigated the effects of cement content and transport distances, highlighting that the environmental benefits of recycling concrete can be offset by higher cement demand due to the larger surface of the coarse recycled aggregates. The boundaries of the investigated process comprise all steps from aggregates extraction (for CC) and building dismantling (for RC) to ready-for-use concrete on the construction site. Recycled mixtures for structural concrete were found to reduce by 30% the environmental impacts computed by means of Eco-indicator 99 (Goedkoop et al. 2000), Ecological scarcity (Frischknecht and Knöpfel 2013) and ADP (Drielsma et al. 2016; Guinee and Heijungs 1995) compared to conventional structural concrete mixtures. The environmental impacts for the GWP resulted similar. For lean concrete, RC mixtures rather than CC lean mixtures evidence a lower contribution to Eco-indicator 99 impact categories and Ecological scarcity by 88-104% and by 80-92% respectively and GWP shows a 30–40 % decrease. The Authors conclude noting that differences between RC and CC mixtures' impacts are due to C&D waste transport distances and landfilling as well as to recovery of co-products (steel scrap). The inclusion of co-products (compared to previous studies) is of great importance for a comprehensive accounting of environmental benefits of RC mixtures. Finally, Tosic et al. (2015) evaluated the environmental impacts of production in Serbia of four types of ready-mixed concrete by means of the LCA approach. They also used the optimization method VIKOR (Opricovic and Tzeng 2007; 2004) to find the optimal solution in terms of concrete type and transport scenario. They included the analysis of economic impacts adopting as criteria the current production costs of ready-mixed concrete in Serbian market. Results show that one of the recycled concrete aggregate alternatives (concrete with a 50% replacement ratio of coarse aggregate with recycled concrete aggregate) is the optimal solution in terms of environmental load, mineral resource depletion and waste production. The natural aggregate concrete alternative is a compromise solution on the basis of economic criteria as it has lower costs of concrete production than RCA. Calculations also suggest the adoption of measures to equal the costs of RCA with the costs of natural aggregate concrete e.g. introducing a tax that increase the cost of river aggregate by 50% and an increase of landfill tax by 53%.

*Environmental impacts of C&D waste management in the end-of-life phase*

The environmental impacts of different processes for C&D waste' treatment as deconstruction/demolition, reuse/recycling, incineration or landfilling have been investigated under several perspectives. Diyamantoglu and Fortuna (2015) assessed the environmental benefits of salvaged materials from deconstructing a residential house in Vermont (USA) and compared different scenarios of reusing/recycling of the salvaged materials versus a baseline scenario. The Authors, by means of WARM model (USEPA 2012a, b) estimated the GHG emissions and energy consumption of five C&D waste scenarios: current practice in USA and in Europe, maximum reuse (all recovered materials to be reused), maximum recycling (all recovered materials to be recycled with no reuse), and soft-stripping reuse (only the materials collected during soft-stripping are reused and the others are recycled). Each scenario involved different resource investments for its implementation, which were accounted for. The highest reduction of GHG emissions and energy use resulted in the scenarios assuming the maximum recycling of salvaged materials and maximum reuse of salvaged materials respectively. They also evaluated the potential economic benefits of salvaged materials and found that their resale total value resulted half of the total costs of purchasing new materials. The price of specific salvaged materials has been estimated equal to the price of new materials as it partially depends on the demand for such materials. The study concludes pointing out to which extent environmental and economic benefits of reusing/recycling salvaged materials are dependent on the way the deconstruction process is carried out (e.g. with higher or lower impacts), on transport distances and on the presence of a resale market for salvaged materials. Martinez et al. (2013) compared the LCA impacts (GWP, human toxicity and non-renewable energy use) of two demolition processes (selective and conventional demolition) based on three management scenarios for C&D waste of a demolished building (Option A: reuse, direct recycling; Option B: treatment before recycling; Option C: final disposal). They found that for scenario B (with selective demolition) the highest relative contribution to GWP (57%) and NRE (54%) comes from transport of waste to treatment plant for recycling and transport to final disposal of non-recyclable fractions. In the conventional demolition scenario the transport to municipal landfill or incinerator generates much higher relative impacts in the GWP (85%) category. La Marca (2010) assessed the environmental impacts of the current transportation scheme of C&D waste from micro-demolitions in the municipality of Rome (Italy) versus an alternative scheme. These waste should be transported from the urban area to the recycling or disposal plants mainly located outside the metropolitan area. She found that with the alternative transportation scheme involving a different route and the use of large full-load vehicles the emissions due to combustion and fuel use of vehicles (CO, $CO_2$, particulate) can be significantly reduced.

Ortiz et al. (2010) compared the environmental impacts of three scenarios (recycling, incineration and landfilling) for the management of construction waste in Cataluña (Spain) by means of an LCA approach. The recycling scenario for seven types of construction waste (stone, metals, plastic, paper and cardboard, wood and others) resulted the recommended option as the contribution to the assessed impact categories is lower compared to landfilling and incineration. In particular recycling and incineration are better than landfilling also considering long distances from the building site to the plant. The Authors recommend the recycling of stone waste "in situ" for reusing them as gravel replacement at the building site. Yuan et al. (2011) apply the emergy analysis approach to compare landfilling and two recycling options (open-loop recycling and close-loop recycling) for concrete waste and found that recycling of concrete waste versus landfilling reduces the environmental loading on the environment. Landfilling induces the heaviest pressure on the environment also considering the results in terms of degradation and loss of ecosystems functions. Marzouk and Azab 2014 analyzed the environmental and economic impacts of recycling and disposal in landfill without collection of C&D waste in Egypt, by means of a system dynamic model and the STELLA software (HPS 1997). Their results show that recycling is a better alternative versus landfilling as it substitutes primary raw materials and reduces the need for landfilling spaces. The simulation over 20 years (the total life time of a C&D Waste landfill) also favors the recycling alternative than a landfilling solution due to potential reductions of concentration of GHG emissions, energy consumption and costs to mitigate air pollution and for the elimination of environmental impacts and human health risks due to uncollected waste. Kucukvar et al. (2014) developed a hybrid LCA model for the assessment of the impacts of three scenarios (recycling, incineration and landfilling) for nine building's C&D waste materials (concrete, wood, nonferrous and ferrous metals, cardboard, plastic, glass, paper, and cardboard). Their results evidence that recycling of ferrous and nonferrous metals, paper, glass and cardboard have a high potential to reduce the impacts in terms of GHG emissions, water and energy footprint compared to the other waste treatment alternatives: incineration with heat recovery and landfilling. Wood, drywall and concrete do not seem to offer the same advantages. Mercante et al. (2012) for recycled wood and cardboard products, found that GHG emissions are bigger than those of corresponding virgin products, as the latter provide a physical storage of carbon that was previously in the atmosphere as a greenhouse gas. For this reason other end-of-life alternative are suggested. These Authors developed a Life Cycle Inventory for

C&D waste management in Spain based on primary data collected from five Spanish sorting plants. They also found that transportation is the stage that generate the highest contribution to the analysed impacts categories in the life cycle of C&D waste (including on-site pre-collection, transport to sorting plant, operations at the sorting plant, recycling of recovered fractions, disposal in landfill).

Dahlbo et al. (2015) integrate MFA with LCA and Environmental life cycle costing (ELCC) to evaluate the environmental impacts (in particular climate change) of the Finnish C&D waste management system. The assessed C&D waste system includes the life cycle phases of pre-treatment, treatment (landfilling) and recovery/utilization for metals, concrete & mineral waste, wood, miscellaneous waste and mixed waste. Results evidence the high contribution to climate change impacts coming from recovery of metals, as well as the energy recovery from Solid Recovered Fuel (SRF) and landfilling. With regard to ELCC the highest revenues and profits originate from the recovery of copper (Cu) and aluminum (Al), from metals and mixed waste and energy recovery of wood and SRF. An overall evaluation of the waste fractions with the three methods highlights e.g. that treatment of wood provides low environmental impacts and medium economic benefits contrary to concrete the treatment of which is only beneficial with regard to material recovery. The Authors point out that wood is the most critical waste fraction in Finnish C&D waste management system for the achievement of European target rate (70% recycling of C&D waste by 2020). It is mainly used for energy recovery and its recycling as a material should increase in an environmental and economic sound manner. Finally Zhu and Chertow (2016) estimated by means of LCA aggregate environmental benefits of waste reuse in five industrial sectors including construction and across industries in Jiangsu province (China). The goal is testing the environmental benefits arising from waste reuse within the incentive policy framework of "Comprehensive Utilization of Resources" (CUR) amended since 1980. The results evidence that at province industrial scale the main environmental benefits from waste reuse are achieved by construction materials sector as many firms and waste input are certified within CUR policy program. The comparison at product scale showed higher environmental benefits in energy use and carbon emissions using waste as input for the process of manufacturing of 1 ton of cement rather than for 1 ton of mortar and 1 ton of concrete as they contain a small amount of cement. The Authors conclude discussing policy implications of their analysis and results in terms of which types of incentives within current CUR policy would increase environmental benefits from waste reuse.

*Economic impacts of C&D waste management*

Multiple economic benefits for enterprises originate from reusing/recycling of C&D waste. For example the recycling of concrete waste increases the competitiveness and public image of enterprises as they reduce their costs of disposal and can further increase revenues by selling recyclable waste (Tam 2009). Benefits from minimizing and recycling concrete waste are investigated by Tam (2009) in a questionnaire survey in Australia and Japan, sent to 423 parties (contractors, consultants, recycling companies, governmental departments and developers). Focus is placed on benefits related to the reduction of the need of new landfill places, natural materials savings, lower project costs due to the use of recycled materials, lower transportation costs due to the implementation of recycling machines on construction site, among others (Tam 2009). The opinion of the respondents about these benefits revealed that the most important ones are considered ''Reducing the need for new landfills'' and ''Saving use of natural materials''.

Some articles analyzed the economic impacts of investments in centers for C&D waste recycling. Srour et al. 2013 for a Lebanon case analyzed costs and benefits of constructing and operating a recycling center. They found that for all the scenarios under different combinations of price of recycled materials and recycling gate fee the investment is very feasible and has a low pay-pack period. They evidenced the need to promote recycling of C&D waste through the establishment of legislation and economic incentives in so discouraging illegal dumping. In particular landfill tipping fees should be higher than recycling gate fees. Zhao et al. (2010) investigated the viability of investments in mobile and fixed Chinese recycling centers with used and new equipments. The Authors show that centers with new equipment are characterized by high fixed costs and low revenues. This reduces the opportunity of profits margin contrary to the centers with used equipment. They ended up giving importance to the implementation of economic instruments (as taxes) to improve the profit margin of recycling centers and reduce the investment risks for investors. Nunes et al. (2009) evaluated the opportunity of adopting a circular approach (reverse logistics) for construction and demolition waste in Brazil. In that country most of the recycling centers are owned by public authorities. In a precedent work they found that most of the assessed recycling center were not adequately administrated by public authorities. The economic viability of recycling center depends on the capacity of public authorities to take decisions about e.g. cost of disposal in landfill sites, costs of transporting C&D waste to landfills and prices of raw materials.

*Barriers and Solutions to the management of C&D waste*

Obstacles of different nature are evidenced and discussed in the literature (Srour et al. 2013; Tam 2009). Dahlbo et al. (2015) notice that main barriers for recycling C&D waste are the high availability and low cost of virgin raw materials, which decrease the demand for recyclate products and the interest in developing business for these products. To enhance reuse/recycling, a reduction of taxes on labor and an increase of taxes on the use of primary raw materials as well as introducing end-of-waste criteria for specific C&D waste fractions could contribute to increase the market for secondary materials from C&D waste (Club of Rome 2015; Monier et al. 2011). Club of Rome (2015) suggests the parallel reform of VAT taxation to exempt goods produced by secondary materials where VAT has already been paid once (Club of Rome 2015). On the other side, Tam (2009) found that the high prices of recycled concrete products and the few uses of these products are in practice the main barriers in Australia and Japan. The Author suggest as a solution a better information about the classification of recycled products (Tam 2009). Gangolells et al. (2015) state that in Catalonia, Spain, the adoption of specific regulations about C&D waste management (promoting on-site waste sorting and the definition of the use of recycled aggregate in structural and non-structural concrete applications) eliminated the problem of uncontrolled dumping and increased reuse/recycling for C&D waste. In the survey carried out by Gangolells et al. (2015), most respondents consider the legal framework not beneficial for their business and inadequate for all size of companies. The economic costs of complying to legal framework as well as the high disposal and treatment fees, lack of environmental awareness, lack of sufficient knowledge about potential reuse/recycling of materials by technicians and lack of motivation by on-site workers emerged as barriers to reuse/recycling of C&D waste. Lu and Yuan (2010) in a survey in China about the Shenzhen's construction industry, found that environmental awareness is considered one of the most important success factors for conducting an effective management of C&D waste along with an adequate policy system and the adoption of an environmental management system.

The main obstacles of implementing the ISO 14001 certification scheme in construction sectors in Turkey and Asian countries are analyzed by Turk (2009). In Asian countries the high costs for ISO implementation and lack of governmental and client support are the main impediments. In Turkey the lack of information about ISO 14001 and lack of skilled personnel provide huge barriers to further implementation. The Authors propose to improve information about ISO 14001 certification through training programs, diffusions of best practices and analysis on case studies. Oydele et al. (2014) for UK show that the main obstacle to the use of recycled products in UK construction industry is related to designers' lack of preference for recycled products in project design. The reason seems due to lack of information about the quality of recycled products that are available for use in construction projects. Other barriers are the negative perception from clients about the capacity of reused/recycled product to perform their function, uncertainty about the durability of recycled products, and their higher costs compared to virgin products even if they are secondary materials. Ajayi et al. (2015) evaluated the reasons underlying the ineffectiveness of the management of C&D waste in the UK context. They evidenced that such ineffectiveness is due to the focus of activities on end-of-pipe solutions instead on preventive solutions. To tackle the increase of C&D waste they suggest a greater attention on design stage and preconstruction stages in the construction industry practices, higher financial viability towards preventive rather than on disposal solutions (landfilling), a legislative approach favoring design stage and a higher knowledge on effective waste management options along with the analysis of cost and benefits of waste preventive measures (establishing minimum preventive standard for design). Addressing sustainable management of C&D waste in China, Duan et al. (2014) suggest the identification and quantification of environmental impacts associated to dumping-dominated disposal, the use of LCA to identify alternative treatment strategies, the improvement of legal framework, higher financial resources and training of human resources. Finally, Da Rocha and Sattler (2009) analyze the reuse process of C&D

waste based on the evaluation of demolition sector in the city of Porto Alegre (Brazil). Ten factors emerged as barriers and opportunities to reuse of C&D waste. The factors have also been compared with the findings of other studies in the literature. The low deconstruction costs, the presence of a market for different types of products from demolition and the trust across the supply chain emerged as opportunities to the reuse process for C&D waste. The negative attitude towards reused products (they are perceived as environmentally friendly but of lower quality), regulation and taxes for C&D waste, information problems in the supply chain of reused products, excess of stock points resulted as barriers. They conclude evidencing that most factors are of economic and social nature compared to legal factors due to the socio-economic context of their case study.

*Discussion and conclusions*

The literature review was based on a large number of studies carrying out life cycle assessments, as well as matter, energy, emergy and economic analyses, where recycled products are compared with products obtained from virgin materials as well as recycling processes are confronted to landfilling and incineration. Recycling resulted a better option from an environmental point of view compared to landfilling and incineration. For some type of C&D waste as wood the recycling as material does not decrease the contribution to climate change (Kucukvar et al. 2014; Mercante et al. 2012). Contrarily, in Finland, the recovery of wood as energy has a high potential to reduce the impact to climate change and it is profitable (Dahlbo et al. 2015). A few studies investigated the environmental impacts over the whole life cycle of a building (cradle to cradle approach) including the reuse/recycle of C&D waste in pre-utilization phase (Proietti et al. 2013; Cuellar-Franca and Azapagic 2012). The choice of reusing e.g. bricks and recycling aggregates as well as the installation of solar energy plants on the roof of a building provides environmental benefits leading to reduce the contribution to the different impact categories such as GWP over the whole life cycle of a building (Proietti et al. 2013).

Recent studies, compared to previous studies, analyzing the environmental profile of recycled concrete aggregates showed methodological advancements related to the inclusion of by-products that favor recycled concrete aggregates versus natural concrete aggregates (Knoeri et al. 2013). Moreover the adoption of new technologies for the processing of gravel opened new recycling opportunities for aggregates and cement paste and the generation of environmental gains compared to the current recycling scheme of gravel (Guignot et al. 2015). The environmental benefits of using recycled products can be offset by the impacts of transport distances and modes of transport (Coelho and Brito 2012; Marinković et al. 2010), although these problems can be overcome by optimizing the management of C&D waste (La Marca 2010).

The choice of favoring deconstruction over demolition is recognized by many authors as an opportunity of salvaging high fractions of materials and products for the subsequent reusing or recycling (Diyamantoglu and Fortuna 2015; Silva et al. 2014; Proietti et al. 2013; Coelho and Brito 2012; Da Rocha and Sattler 2009; Bianchi 2008).

The price for most salvaged products is lower compared to the price of new products (Diyamantoglu and Fortuna 2015; Da Rocha and Sattler 2009). In emerging countries as Brazil these products are the only material option affordable for low-income people for the construction of their buildings (Da Rocha and Sattler 2009). Nevertheless the price of specific salvaged products can be higher than the one of new products as they are appreciated for their fashionable and historical value (Diyamantoglu and Fortuna 2015; Da Rocha and Sattler 2009).

Reuse is considered a better option than recycling in waste hierarchies of EU and USA. As a consequence it is essential to shift the attention of research to the analysis of environmental and economic impacts of reusing C&D waste rather than recycling as we found a few studies investigated reuse as an end-of-life option (Diyamantoglu and Fortuna 2015; Da Rocha and Sattler 2009).

Economic benefits arise from recycling concrete waste contributing to improve the competitiveness and public image of enterprises by reducing their costs of disposal and further enhance revenues by selling recyclable waste (Tam 2009).

Studies also evidence the higher prices of recycled products such as recycled concrete aggregates compared to products obtained from virgin materials and suggest the introduction of taxes on natural resources' use and landfill charges to increase virgin materials' prices and encourage the use of recycled products (Dahlbo et al. 2015; Tosic et al. 2015; Monier et al. 2011). A reform of VAT taxation that exempts goods produced by secondary materials where VAT has already been paid once is also proposed (Club of Rome 2015) along with the adoption of instruments that differentiate between alternative reuse processes for the purpose of directing waste to the process that provides the greatest environmental benefits (Zhu and Chertow 2016; Dinan 1993).

From our review it seems to emerge that a circular economy approach in the C&D sector is mainly concerned with the management of its waste. Circular economy is much more than this because it is a new paradigm of development implying to rethink economic process and activities within the ecological limits of the planet (Ghisellini et al. 2016). It looks for innovating the entire chain of production, consumption, distribution and recovery of products according to a cradle to cradle vision (Genovese et al. 2015; Chiaroni and Chiesa 2014). This implies that design phase of a building is crucial as it should take into account all the input and output of the whole life cycle (Osmani et al. 2008). The positive attitude of designers towards the circular economy is fundamental to stimulate the transition to CE among all the actors involved in construction and demolition sector (Altamura 2013). The results of a survey in UK revealed that designers lack of preference to recycled products due to incorrect information about the quality of those products (Oydele et al. 2014). At this regard e.g. a better classification of recycled aggregates for their use in structural applications is considered by some Authors a factor able to improve the knowledge about the quality of recycled aggregates and boost stakeholder's confidence (Silva et al. 2014).

The results of the review presented in this article clearly show that the adoption of a circular economy is feasible and desirable from an environmental and economic point of view in C&D sector. CE reduces the impacts to the environment improving its quality and enhances the competitiveness of enterprises. Given the environmental challenges, the high exploitation of virgin materials as well as their waste, we conclude suggesting the need to incentivize at political level the transition towards CE in this sector to overcome the different types of barriers, in particular economic, that hamper its further development. The transition from the current model of economic systems to a circular economic systems implies the recognition of the important economic functions provided by environment as theorized by Pearce and Turner (1993). In the current economic system there is neither a price nor a market for environmental goods (such as air and water quality) even if they have a clear value or utility for individuals and societies (Ghisellini et al. 2016). Hence there is the need to adopt instruments and policies that recognizes the better environmental quality envisaged in CE's practices such as cleaner production processes, renewable energy sources' use, reused/recycled products and reuse/recycling processes.

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# CHAPTER 10 - URBAN ENERGY METABOLISM

Cities are the engine of economic development and human wellbeing, but their dynamics needs to be supported by the convergence of large flows of material and energy resources. Assessing a city resource metabolism becomes increasingly crucial, not only concerning the relation with the environment as a source or a sink, but also concerning the internal dynamics of resource exchange among city components and sectors.

Over the last few years, there has been an increased interest in cities and their energy use – driven in part by climate change concerns.

Cities have a central role to play in the reduction of CO2 emissions and the fight against climate change, the historic challenge now facing our society. Buildings are the largest energy-consuming sector in the EU, and offer the largest cost-effective opportunity for savings.

In this Chapter we compare a number of Italian cities (Roma, Napoli, and a few smaller ones in the Campania region, namely Ischia, Massa Lubrense and Vico Equense) as well as a megacity in China (Beijing). We also plan to include Barcelona (Spain) in the comparison, but the assessment of its metabolism by the UAB team is planned for the end of the year 2017, according to the working plan of the EUFORIE Project. The full comparison will, therefore, only be available by the end of 2017.

However, the presently available evaluations already provide a sufficient picture of how biophysical indicators can be used to assess the energy and material use by an urban system and therefore support deeper studies to increase efficiency, in so also decreasing consumption and environmental impact.

The present Chapter deals with:

Chapter 10.a Indicators of resource efficiency, environmental loading and sustainability of urban systems. An emergy-based environmental footprint.

Chapter 10.b Monitoring trends of urban development and environmental impact of Beijing, 1999–2006

# CHAPTER 10.a Indicators of resource efficiency, environmental loading and sustainability of urban systems. An emergy-based environmental footprint.

**Key for abbreviations**

| Abbreviation | Definition | Abbreviation | Definition |
|---|---|---|---|
| %REN | Renewable fraction of emergy use | LCAF | Legal Concentration Amplification Factor |
| AA | Actual Area | LCDA | Legal Concentration Dilution Area |
| ASA | Absolute Sustainability Area | $LS_N$ | Renewable fraction of Labor and Services input |
| ASAF | Absolute Sustainability Amplification Factor | $LS_R$ | Non-renewable fraction of Labor and Services input |
| BCAF | Background Concentration Amplification Factor | $M_{dil}$ | Mass of dilution air or water needed |
| BCDA | Background Concentration Dilution Area | MFA | Material Flow Analysis |
| CED | Cumulative Energy Demand | N | Local non-renewable input |
| DA | Dilution Area | NEAD | National Environmental Accounting Database |
| ED | Empower Density | PEDI | Pollutant Empower Density Index |
| $ED_{ren}$ | Renewable Empower Density | R | Renewable input |
| ELR | Environmental Loading Ratio | RLA | Relative Loading Area |
| EMA | Emergy Accounting | RLAF | Relative Loading Amplification Factor |
| ESI | Emergy Sustainability Index | RSA | Relative Sustainability Area |
| EYR | Emergy Yield Ratio | RSAF | Relative Sustainability Amplification Factor |
| F | Input from economy (imported) | TRA | Total Renewability Area |
| $F_1$ | Imported fuels and electricity | TRAF | Total Renewability Amplification Factor |
| $F_2$ | Imported food and water | U | Total emergy |
| $F_3$ | Other imported goods | UEV | Unit Emergy Value |
| LCA | Life Cycle Assessment | W | Downstream environmental impacts |

In this chapter we studied a sample of Italian cities (Rome, Naples and other three minor cities in Campania region) to explore how existing data can be used to understand the role played by energy demand and energy quality and finally identify the present energy efficiency and the phases where efficiency drops occur.

We applied the Emergy Accounting (EMA) and Cumulative Energy Demand (CED) methods within an LCA framework, to develop and validate indicators of urban environmental sustainability and efficiency, using as case studies five urban systems of different size in Italy. CED allowed an assessment of the commercial energy consumption required on local and global scales to support the city life and economy. Airborne emissions related to direct and indirect energy consumption were also assessed. EMA was used to quantify the environmental support required for the urban metabolism, in terms of resource generation and ecosystem services supply. Combining these three aspects, a new metric is discussed and developed to estimate the environmental impact of cities, with reference to their resource use, in order to implement comprehensive indicators and suggest resource use criteria at urban level. A city's support area to buffer upstream and downstream environmental loading is also calculated. Relative and absolute sustainability concepts are introduced and discussed, showing how far the investigated cities are from a resource-based environmentally sustainable state. Finally, practices are suggested as an exit strategy from the present intensive fossil powered economy towards a higher level of environmental sustainability and wellbeing.

Globally, more people live in urban areas than in rural areas, with 54% of the world's population residing in urban areas in 2014 and many more expected in the next years. According the UN – World Urbanization Prospects (2014), in 1950 30% of the world's population was urban, and by 2050, 66 per cent of the world's population is projected to be urban.

This trend will affect the sustainability of urban systems that will have to cope with an increase in resource consumption, energy demand and waste disposal necessity in the near future.

Unless energy efficiency and renewable energy implementation as well as material recycling patterns (circular economy) develop quickly and effectively, urban areas will require in the near future an increasing amount of energy and material resources to support its development, population growth and activities (Holmes and Pincetl, 2012). A city can be compared to an organism that requires resources to live (support and develop) and releases waste flows resulting from its metabolic processes (Samaniego and Moses, 2008). Monitoring inflows and outflows and understanding how they relate to resource availability and environmental carrying capacity is crucial for aware and concerned urban sustainability policies.

Although cities cover less than 2% of the earth's surface, they consume about 78% of the energy available on the planet, to which one must add the amount of material products (food, building materials, metals, etc.) that indirectly require energy consumption. This figure can be explained in economic and social terms, as cities offer residents new opportunities for business, education, security, social life. Supporting these activities require significant flows of resources, resulting in an environmental stress both locally and globally.

The report "Urban Development Overview" commissioned by the World Bank (2014) points out that the most urbanized region is North America with 82% of the population living in urban areas while the regions of Asia and Africa have lower values, respectively 48% and 40%, although with higher urbanization rates. According to the same report, most megacities and large cities are located in the southern hemisphere. In Italy, the majority of population (44, 6 %) live in highly populated cities whose population density is over 500 inhabitant per $km^2$, very close to the European value (47%). The most populated Italian regions are Campania, Lombardia, Liguria and Lazio.

In the last decades, the environmental sustainability of urban areas has been a topic of discussion both in the scientific world (Satterthwaite, 1997; Newman and Kenworthy, 1999; Decker et al., 2000; Liu et al., 2009; Schremmer et al., 2011) as well as policy debates (UN, 2013) due to the crucial link among growth, natural resources exploitation (use of non-renewable energy and materials) and consequences on the state of the environment. Urban systems have been widely investigated by means of several different approaches. Kennedy et al. (2014) introduced a set of indicators designed for gathering information about the definition, biophysical characteristics, and metabolic flows of cities. This indicator set was recently used by Kennedy et al. (2015) to quantify the energy and material flows through the world's megacities with populations greater than 10 million people as of 2010. Performance indicators for cities, regions and nations have been developed, based on well-known assessment methods, sometimes integrated into a specific toolkit: embodied energy, material flow analysis (MFA), life-cycle analysis (LCA), $CO_2$ emissions, and economic returns (Yong et al., 2012). These indicators individually or in combination do not necessarily provide a fully adequate characterization of an urban system environmental integrity and resource use, since they were not designed to assess whole-systems, closed-loops, and feedback features that are key characteristics of a circular economy (Yong et al., 2013). For this reason, most of them disregard flow quality and characteristics as well as the complexity of interactions between the natural environment and socioeconomic systems (Huang et al., 2006). In this study, we address urban sustainability by means of the emergy approach. Emergy (a measure of the cumulative environmental support to a process) is a unifying metric into which the diversity of energy and material flows within a city can be translated and combined in a meaningful way, preserving information on both their quantity and quality, taking into account time, environmental services, human labor, renewability, concentration and resource exchange dynamics. In so doing, mono-dimensional assessments are avoided and the complexity of real systems is properly accounted for.

Emergy Accounting method (EMA) is a biophysical accounting method based on the concept of environmental quality of resources (a measure of the cumulative environmental work to generate them) and focused on the study of natural and human-dominated ecosystems from a "donor-side" point of view (Odum 1996). EMA is increasingly applied to evaluate urban sustainability: Macao and Beijing in China (Zhang et al., 2011; Liu et al., 2011), Montreal in Canada (Vega-Azamar et al., 2013), Uppsala in Sweden (Russo et al., 2014) and Rome in Italy (Ascione et al., 2008, 2009, 2011; Zucaro et al., 2014) among others. Although the full range of applicability options of EMA still needs to be better explored, Lou et al. (2015) showed asthe EMA can be a suitable tool for investigation, comparison and design of regional sustainability and can be proposed as a very effective tool to complement the usual economic and energy analyses. Lou et al. (2015) provide a set of performance and sustainability indicators that can be used for evaluation and comparison of other Chinese and worldwide cities and development areas. EMA's ability to evaluate downstream impacts of productive activities was also demonstrated by Brown (2008), who introduced a Pollutant Empower Density Index (PEDI) considering the flux of the pollutant and the productivity of the background environment. Such PEDI can also be applied to urban systems and provides a downstream understanding of the impacts of concentrated use of resources.

The aim of the present study is both to evaluate the environmental performance of selected urban systems in Italy and to provide a methodology development in order to generate consistent environmental sustainability indicators.

*The investigated urban systems*

This study analyzes selected urban systems located in the Lazio and Campania regions (central Italy): Roma, Napoli, Vico Equense, Massa Lubrense and Ischia. These urban systems are characterized by very different spatial scales, population size and economic structures. Rome and Napoli, as large urban systems, require much higher material and energy flows than the other three municipalities taken into account. One of the goals of the present study is also to ascertain how the impacts of the supply chain to these urban systems is related to their size in terms of area, population and lifestyles. Their location in Italy is shown in Figure 1.

Rome, one of the largest European cities, is characterized by a very high landscape complexity due to the presence of 70 $km^2$ with buildings and ruins of historical interest intertwined with about 356 $km^2$ densely urbanized with modern buildings, 410 $km^2$ of environmentally protected areas, 410 $km^2$ of agricultural land, 44 $km^2$ of industrial areas, an average elevation of 21 m and 20 km of coastline. Rome is the capital of Italy and the Lazio region. Complexity is also increased by Rome being the capital of Italy, by the presence of the Vatican State as an attraction for religious events and pilgrims, as well as by its huge artistic patrimony. The cultural complexity of Rome attracts tourists (with tourism being one of the most important economic sectors) but requires significant investment for maintenance. The 2.9 million residents in 1,290 $km^2$ of urban territory and 4.3 million inhabitants in the larger Metropolitan City area (5,352 $km^2$) recently installed by the national Law for Roma Capitale (1 January 2015), make Rome the country's largest and most populated city. The original Rome landscape was a hilly area with wetlands, crossed by the Tiber River, which affected and still affects the urban development and the physical features of the city. Our study only focuses on the inner urban territory, not the entire Metropolitan City since, due to the recent institution of the latter administrative entity, data of the larger area are not yet fully available.

Napoli is the regional capital of Campania Region. The urban area covers approximately 120 $km^2$ and has an average altitude of about 20 m. The territory is predominantly hilly. Although the city has a very limited surface extension, it has a significant value of population density (about 8,000 inhabitants / $km^2$), the highest among the major Italian cities. For the year of investigation, 2011, the population of the inner city administrative boundaries was of 961,106 units, with small growth in recent years up to 975,260 inhabitants in the year 2015. The Metropolitan City of Napoli includes 3.1 million people within an area of 1,171 $km^2$. The city has a developed tertiary sector (administrative structures, local and regional government, schools and universities, accommodation and commercial activities) and poor primary and secondary sectors. This study was limited to the administrative boundariesof the cities.

Vico Equense is situated on the top of the Sorrento coast, among the Lattari Mountains and the Gulf of Napoli. It has an area of 30 $km^2$, making it the municipality with most extension of the peninsula and the eighth in the province of Napoli. The resident population in 2005 was made up of 20,048 inhabitants. The natural value of the area and the accommodation capacity make tourism the leading sector of the municipality comprising 55% of the urban economy. In reference to the agricultural sector, Vico Equense is famous for the production of two commodities: the extra virgin olive oil and the Sorrento lemon. Industrial activities are characterized by small craft enterprises, operating mainly in the sectors of agro-food, crafts, agriculture and livestock.

Massa Lubrense is on the end of the Sorrento coast, bordering the Amalfi coast. The municipality covers an area of 19 $km^2$ and has a population reviewed in 2005 of 13,434 inhabitants. Agricultural activity is prosperous and characterized by lemon, wine, oil and fruit production. The large employment in hotels and trade confirms the strong tourist vocation of the territory. The manufacturing sector consists mainly of factories that process agricultural products.

The municipality of Ischia is one of the six municipalities of the homonymous island. It is located in the archipelago of Phlegrean islands in northern end of the Gulf of Napoli. It has a territorial extension of 8 $km^2$ and a resident population of 18,695 inhabitants in 2012. The district is characterized exclusively by the activities of the tourism sector due to bathing and thermal attractions. The island is a summer destination of thousands of Italian and foreign tourists for both natural landscapes and for the spa facilities, whose waters are known and used since ancient times, and recently have achieved great national and international importance for the beneficial properties. Agriculture for years has been the main source of employment on the island, then replaced by tourism in recent years, while fishing and seafaring activities, traditionally, have been less important.

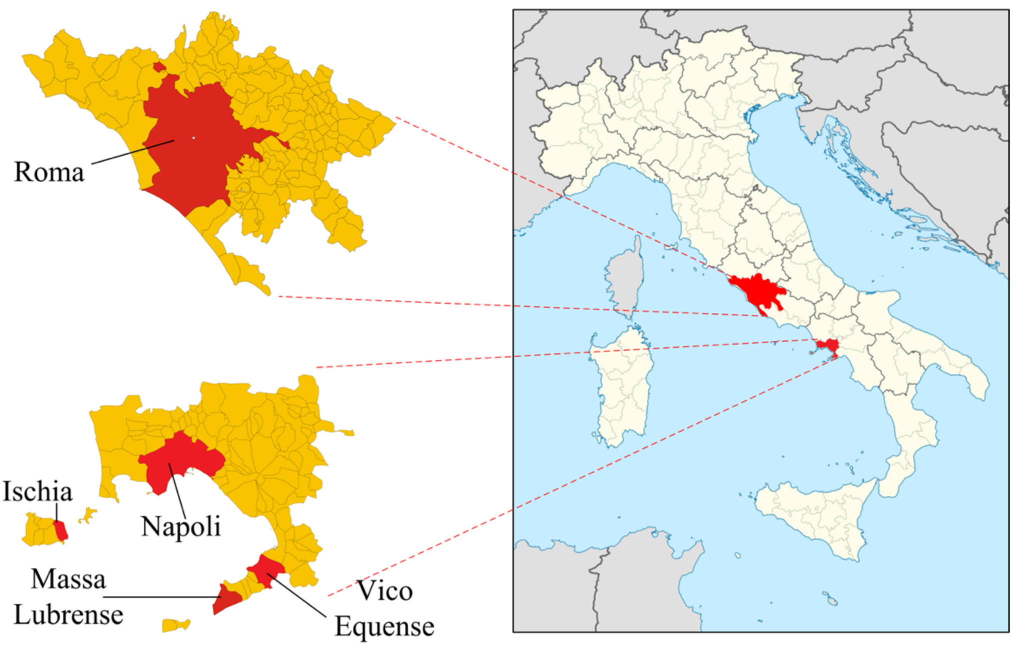


**Figure 1**. The investigated urban systems.

Figures 2.a and 2.b show area, population, GDP, population density and income per capita of the five investigated urban systems. Data used to implement the analysis were mainly taken from the official statistical offices of the municipalities and from the statistical databases produced by Eurostat (Camera di Commercio di Napoli, 2013; Comune di Napoli, 2012, 2013; Eurostat, 2010, 2013; Comune di Roma, 2012); they are referred to the year 2011. It is worth putting into evidence the huge difference between extensive indicators (Area, Population and GDP), that are related to size, and intensive indicators, that suggest a link to lifestyles and land as potentially limiting factor. Extensive indicators show Rome always ranking first and Massa in the last position. Intensive indicators provide instead a different ranking as far as both amounts and positions are concerned. While income per capita in the highest ranking system (Roma) is doubled compared to the lowest ranking (Massa), population density shows a picture in which the highest ranking (Napoli) is four times higher than the second one (Ischia) and twelve times higher than the lowest ranking (Massa).

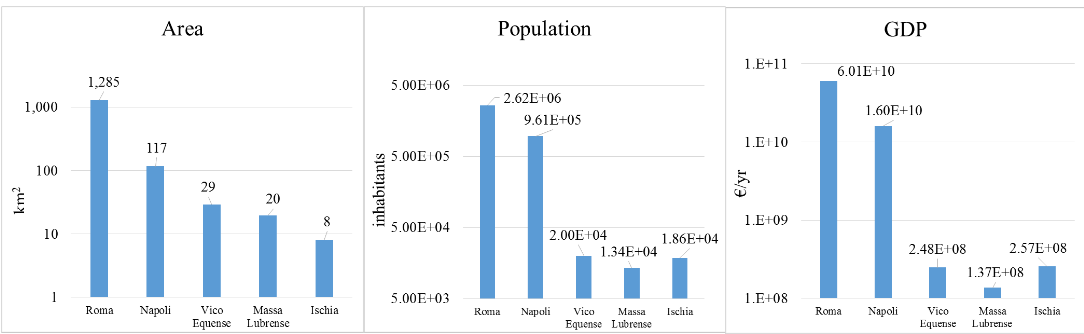


**Figure 2.a** Area (km$^2$), Population (number of inhabitants) and GDP (€, calculated with the income approach) of the investigated municipalities for the year 2011. Axes are in logarithmic scale.

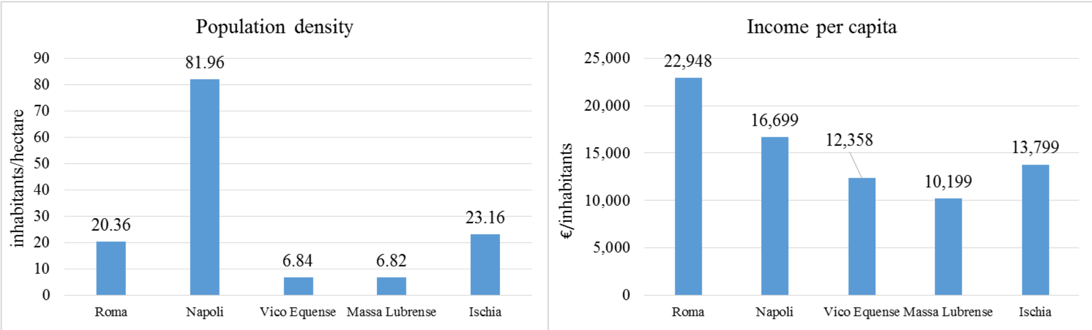


**Figure 2.b** Population density (number of inhabitants per hectare) and income per capita (€ per inhabitant) of the investigated municipalities for the year 2011.

*The methods*

Investigating only the behavior of a single process or seeking maximization of one parameter (efficiency, production cost, jobs, etc.) is unlikely to provide sufficient insight to adequately support policy-making intended to promote sustainability of a complex coupled social-ecological system like a city. In this paper, the Emergy Accounting method (EMA) (Odum, 1996; Brown and Ulgiati, 2004) is applied and further developed. Moreover, the Cumulative Energy Demand (CED) (Slesser, 1978; Smil, 1991; Hishier et al., 2010) method and an emission accounting procedure are also used to build with EMA more comprehensive sustainability indicators. The administrative boundaries of the cities were taken as reference for the spatial boundaries of the investigated systems.

*Cumulative Energy Demand (CED)*

CED allowed estimating the direct and indirect commercial energy and material requirements by converting them into units of oil equivalent (grams of oil equivalents or Joules). Fossil and nuclear energy flows as well as renewable energy flows under human control (hydroelectricity, geothermal, photovoltaic and wind electricity as well as biomass energy) were accounted for. Instead, CED does not include those energy forms that support an economy in the form of environmental services (for example, the solar energy supporting wilderness and agricultural photosynthesis). The $CED_i$ related to the *i-th* renewable or nonrenewable input to a process ($E_i$) was calculated by multiplying the raw amount $E_i$ by its cumulative energy intensity factor $c_i$ (Equation 1):

$$CED_i = c_i * E_i \qquad \text{(Eq. 1)}$$

Finally, the total CED of the system S was calculated as

$$\mathrm{CED}_{\mathrm{system}} = \sum_i CED_i \qquad \text{(Eq. 2)}$$

The total $CED_{system}$ was divided by the number of inhabitants or the GDP of a city to produce energy related intensities of the main city features, namely population and economic product. In this paper direct and indirect fossil energy consumption were also used to estimate the gaseous emissions ($CO_2$, CO, $N_2O$, $NO_x$, $SO_x$, $CH_4$) generated both at local and global scale by the urban system (transport, household, other forms of energy uses).
The cumulative mass of each kind of emission released by the city processes, $W_c$, was roughly estimated, on a yearly basis, by means of a calculation procedure expressed in the following equation (3):

$$W_c = \sum f_i * w_i \qquad i = 1,\ldots,n \qquad \text{(Eq. 3)}$$

Where $f_i$ is the $i^{th}$ input flow of energy to the process and $w_i$ is the mass of emission associated to the flow $f_i$, that includes emissions from local and outside processes. The resulting cumulative mass of emissions is the sum of local emissions and emissions released elsewhere over the supply chain. In this paper, the two scales were kept separated to investigate the global to local ratio of these impacts.
Emission values were used to analyze the level of downstream environmental impact, expressed as area needed to dilute their concentration and alleviate the local environmental burdenby spreading chemical flows to a larger, less populated area.

*Emergy-based indicators of urban sustainability*

The global ecosystem provides a wide range of benefits (ecosystems services) to the socio-economic system. In particular, ecosystem services were classified into four categories: Provisioning services (food, raw materials, fresh water, medicinal resources); Regulating services (local climate and air quality regulation, carbon sequestration and storage, moderation of extreme events, waste-water treatment, erosion prevention and maintenance of soil fertility, pollination, biological control); Habitat or Supporting services (habitat for species, maintenance of genetic diversity); and, finally, Cultural services (recreation, mental and physical health, tourism, aesthetic appreciation and inspiration for culture, art and design, spiritual experience and sense of place) (Millennium Ecosystem assessment 2005; TEEB, 2011). All of these services are in turn supported by the main biosphere driving forces contributing to the total emergy baseline, identified as solar insolation, geothermal heat and gravitational potential (Brown et al., 2016). Therefore, resources and ecosystem services were quantified in terms of the emergy supporting their provision.
The potential of an environment to provide services and materials is often referred to as an "environment's source function", and this function is depleted as resources are consumed or pollution contaminates the resources. The "sink function" describes an environment's ability to absorb and render harmless waste and pollution (Harris. 2006).In particular, for the purpose of this study, we refer to the geobiosphere as the source of all material and energy input feeding the economic subsystem and the sink for all its waste flows. Figure 3 is a simplified energy system diagram showing the

aggregated flows (R for renewables, N for local non-renewables, F for imported resources, and $LS_N$ and $LS_R$ for the non-renewable and the renewable fraction of labor and services), all supporting the life of a city. A key for symbols is provided in the Appendix. While all these flows are directly and indirectly related to the source function of Nature, the flow $R_1$ in the diagram represent the ecosystem services associated to the sink function. As supporting flows are not only from the local region, also the additional emergy required to dilute the downstream environmental impacts generated by the city cannot be only available locally, but also operates at larger scales.

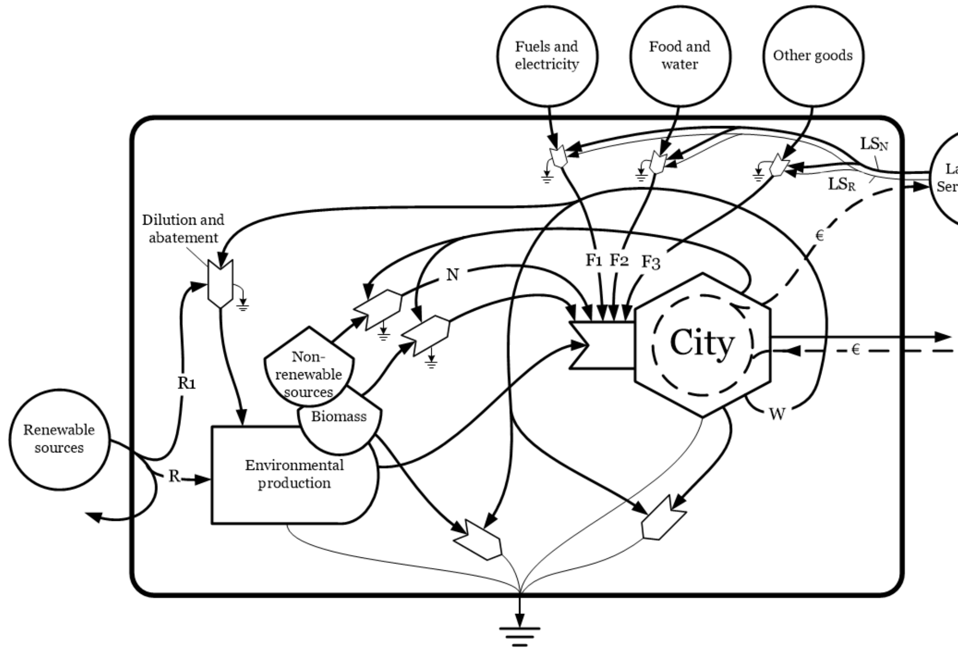


**Figure 3**. Simplified energy system diagram of a city (R for renewables, $R_1$ for additional emergy required to dilute the downstream environmental impacts of the city, N for local non-renewables, $F_1$ for imported energy, $F_2$ for imported food and water, $F_3$ for other goods, $LS_N$ and $LS_R$ for the non-renewable and the renewable fraction of labor and services respectively, W for downstream environmental impacts.

*A performance-oriented approach: Emergy-based indicators of urban systems*

A set of indices and ratios suitable for policymaking (Ulgiati and Brown, 1998; Brown and Ulgiati, 1999, 2004a,b) were calculated:

(1) Total emergy, $U = R + N + F + LS_R$ and $LS_N$. It measures the convergence of renewable (R), nonrenewable (N) and imported (F, $LS_R$ and $LS_N$) emergy to support the city.

(2a) Population emergy intensity = U/inhabitants. It measures how much emergy it takes to support one average person, regardless of whether the input is renewable or not.

(2b) Currency emergy intensity = U/GDP. It measures how much emergy it takes to generate an average unit of money in a given year.

(3) Emergy yield ratio, $EYR = (R + N + F + LS_R + LS_N)/(F + LS_R + LS_N)$. It is a measure of the ability of a process to exploit and make available locally renewable (R) and nonrenewable (N) resources by investing outside resources (F and LS). It is an index sensitive to the alternative local-imported and it is of crucial importance for an urban system.
(4) Environmental loading ratio, $ELR = (N + F + LS_N)/(R + LS_R)$. It compares the amount of nonrenewable (N) and imported (F and $LS_N$) emergy to the amount of locally renewable emergy sources ($R+LS_R$). In a way, the ELR is a measure of the possible disturbance to the environmental dynamics, generated by the local development driven from outside sources. The ELR is clearly able to make a difference between nonrenewable and renewable resources, thus complementing the information that is provided by the emergy intensities.
(5) Renewable Fraction of emergy use, %REN = R/U, the fraction of emergy that is from local or imported renewable sources.
(6) Emergy Sustainability Index, ESI = EYR/ELR. It is an aggregated indicator of sustainability that links the characteristics of the EYR (sensitive to the outside-versus-local emergy alternative) and the ELR (sensitive to the nonrenewable-versus-renewable emergy alternative). It responds to the goal of relying on the largest possible amount of local resources in a process at the lowest possible environmental loading locally and elsewhere.

*A downstream-oriented approach: The emergy cost of emission dilution and waste treatment*

In every process of urban life, resources are degraded and generate solid waste and emissions. Solid waste are most often dealt with by means of disposal procedures and the treatment costs are accounted for and charged to each process. Instead, except for a very few cases, urban emissions are most often not accounted for and their treatment is left to the environment, in the form of an additional demand for ecosystem services. Ulgiati and Brown (2002) proposed a procedure to calculate the emergy support for the dilution and abatement ($R_1$ in Figure 3) of airborne and waterborne heat and chemical emissions (W in Figure 3), developing a "downstream-oriented" emergy accounting. Their procedure stems from the quantification of the mass of air or water needed for the dilution of the emissions to the desired concentration. This "control mass" is assumed to cross the area where the emissions are released and spread them through a larger area at lower concentration. The quantification of such environmental service is based on the kinetic energy of the wind or current in the water body, to be in turn used to compute the emergy flow supporting the dilution process. It is worth noting that linking the environmental service to a dilution process translates into a simplified model of the interaction of the emission source and the environment, affected by a large uncertainty about the way emissions are actually uptaken, diluted or abated via the complex sequence of chemical reactions within atmosphere, water bodies and soil. However, the "control mass" model, although likely under-estimating the amount of environmental services actually needed, at least provides a reference

value for comparison of different systems and potential improvements in their resource use.
The volume of air (or water) needed for emissions dilution (down to the biosphere background level or, at least, down to the threshold required by the enforced laws) was calculated:

$$M_{dil} = d * \frac{W}{c} \qquad \text{(Eq. 4)}$$

where $M_{dil}$ is the mass of dilution air or water needed, d is air density (1.23 g/dm$^3$ for air, 1.0 g/dm$^3$ for water), W is the amount of a given emission from the city (with appropriate units), and c is the acceptable concentration according to legal limits or to Environmental Protection Agencies or the background concentration of the biosphere. Non-$CO_2$ emissions used in this study as well as legal and background concentrations of pollutants are indicated in the Appendix, Table A.2. We have computed the amount for each emission and then take the largest amount as the controlling pollutant.
Limiting to airborne pollutants (waterborne emissions can be treated in a like manner), the kinetic energy of the mass of dilution air was calculated from the following equation:

$$K = M_{dil} * \frac{v^2}{2} \qquad \text{(Eq. 5)}$$

where K is kinetic energy and v is the average wind speed in the region. When kinetic energy (K) is multiplied by the transformity of the wind ($tr_{wind}$), it gives a measure of the environmental service ($R_1$) that is required, in emergy units (sej):

$$R_1 = K * tr_{wind} \qquad \text{(Eq. 6)}$$

Once the required emergy to dilute emissions ($R_1$) was calculated, the Dilution Area (DA) needed to generate $R_1$ was determined. DA should not be considered an actual area around the emission point, but instead a virtual area that needs to be set aside (undeveloped) somewhere for the provision of enough ecosystem services (growth of trees, evapotranspiration, wind capture, etc.) to compensate the loading caused by the emissions. If such compensation does not occur, the process is not sustainable, that is there is not enough environmental support to take care of its impacts. DA was defined as "virtual" because, unfortunately, the areas actually available for the generation of ecosystem services are shrinking and therefore become day-by-day unavailable in practice. DA wass computed based on Equation 7:

$$DA = \frac{R_1}{ED_{ren}} \qquad \text{(Eq. 7)}$$

where $ED_{ren}$ is the renewable empower density in the area, namely the amount of renewable emergy that is available per unit of area and time ($sej*m^{-2}*yr^{-1}$). $ED_{ren}$ is a location specific parameter calculated from the analysis of the larger region (or nation) in which the city is located. When the coefficient "c" (Eq. 4) is set equal to the permitted legal concentration of a given emission a *Legal Concentration Dilution Area* (LCDA) is calculated; in a like manner, when "c" is set equal to the natural background concentration the *Background Concentration Dilution Area* (BCDA) can be calculated.
The two values, LCDA and BCDA, were calculated by referring to the local emissions within the city (e.g. fuel combustion in transport) or to the entire amount of emissions over the supply chain of goods provided to the city (e.g. emissions by power plants providing electricity to the city). Depending on the choice of scale, $LCDA_1$ and $BCDA_1$ needed to dilute emissions released locally as well as $LCDA_2$ and $BCDA_2$ for the emissions released at larger scale can be calculated.

*An upstream-oriented approach: Calculating emergy-based support areas for urban systems*

The virtual area DA for emission dilution constitutes, as already mentioned, a downstream-oriented environmental support to a process, in that it is linked to the amount of emissions released. However, processes cannot occur if upstream resource flows are not made available. Within the emergy approach framework, a mix of locally renewable (R) and nonrenewable (N) as well as imported from outside (F) resources is needed for a process to occur. These resources are generated by the present ecosystem activity (the flow R) as well as by the past dynamics that created resource storages (natural capital, such as oil, mineral reservoirs, standing forests). Brown and Ulgiati (2001) firstly introduced an emergy based "renewable carrying capacity" of a given human-dominated system as the land area required to support an economic activity as if all the resources were generated by the present ecosystem services, without reliance on nonrenewable storages. In their "upstream-oriented" emergy accounting, focused on the amount and quality of resources supporting a process, Brown and Ulgiati (2001) identified a *Total Renewability Area* (TRA), to be calculated by dividing the local (N) and imported ($F + LS_N$) nonrenewable emergy input to a system, by the average renewable empower density $ED_{ren}$ of the region in which the system is located:

$$TRA = \frac{N+F+LS_N}{ED_{ren}} \qquad \text{(Eq. 8)}$$

TRA is a buffer land that would be required if the socio-economic activities were driven only by the local renewable emergy sources. According to Brown and Ulgiati (2001) TRA is a measure of environmental carrying capacity because it indicates the necessity for a support area commensurate to resource demand, thereby placing an environmental limit to potential development. Based on the definition of TRA, Brown and Ulgiati (2001) suggested to compare the ELR of the system with the ELR of the country's economy where the system is embedded. The constraint to be imposed was:

$$ELR_{system} \leq ELR_{country} \quad \text{(Eq. 9)}$$

Under this constraint, when a system generates an environmentalload that is lower than the average of the country's economy, the new activity does not generate a worsening of the present state of the environment, as far as renewability is concerned. From Eq. 9, an emergy value of renewable emergy demand ($R_2$) and a *Relative Loading Area* (RLA) can be calculated, consistent with the actual environmental loading ratio of the country's economy.

A direct follow-up of Brown and Ulgiati (2001), published by Lou et al. (2015), was the possibility to impose a stronger sustainability constraint based on the Emergy Sustainability Index (ESI), which includes both the sustainability from a local self-reliance point of view (EYR) and the sustainability from the environmental loading point of view (ELR):

$$ESI_{system} \geq ESI_{country} \quad \text{(Eq. 10)}$$

where $ESI_{country}$ is the ESI of national economy. Eq. 10 provides a different way to calculate the support emergy needed, $R_3$. In a like manner with the previous Eq. 9, a *Relative Sustainability Area* (RSA) is defined as the support area required to capture the renewable emergy $R_3$, under the condition that the ESI of the investigated system is at least equal to the ESI of the country.

Calculations translate into a larger demand for support area than available, to capture more renewable emergy, decrease the loading ratio ELR and increase the EYR. The approach is sensitive to the large-scale performance of the economy and therefore provides an indicator of Relative Sustainability, defined as the condition when a process does not worsen the present country's performance.

The National Environmental Accounting Database (NEAD) (http://www.cep.ees.ufl.edu/emergy/nead.shtml), a collection of emergy flows and indicators of the majority of world countries, was designed in 2003 (and further updated in 2010) by the Center for Environmental Policy, University of Florida. The NEAD's goal was to help research and teaching of emergy systems theory based on the comparison of the main emergy indicators over time. According to NEAD, the national ESI values in the world, calculated for the year 2008 were all lower than 10. In detail, the country with highest 2008 ESI value was Guyana (ESI=8.7), followed by Suriname, Argentina, Madagascar, Guinea, Bolivia, Ethiopia, Iceland, Niger, and Canada (Liu et al., 2016). Therefore, a reasonable reference value for a fully, ideally sustainable economy can be set as ESI= 10. The following equation represents the constraint to assess the distance of the urban system under study from a conventional environmentally sustainable economy reference:

$$ESI_{system} = 10 \quad \text{(Eq. 11)}$$

Consequently, Eqs. 10 and 11 allow to compute the Absolute Sustainability Area (ASA) required to capture the renewable emergy $R_4$ necessary to reach the highest possible level of environmental sustainability. ASA is a measure of absolute sustainability independent on the country's economy where the system is embedded. Such values of environmental and resource-based sustainability, however, need to be integrated by a careful assessment of lifestyles in each country, to ascertain how resource availability and wellbeing are linked.

*Results*

*Energy consumption and energy efficiency parameters for the economy*

Firstly, an assessment of energy uses in the investigated urban systems was performed to become the starting point of the study. Main results of the energy assessment are presented in Table 1. Commercial energy expenditures of the investigated urban systems, listed in Table 1, include all energy uses (also from renewable sources captured through technological devices, measured as oil equivalents) at local scale as well as at the larger scale of the supply chain where resources and goods come from. Data depend, of course, on the systems' size and characteristics (population, lifestyles), but are not linearly proportional to population size. For example, the population of Roma is about 2.8 times the population of Napoli and more than 100 times the population of the other urban systems in this study, but its local energy consumption is respectively 3.8 times higher than for Napoli, more than 300 times higher than for Vico and Massa, and finally 1.3 time higher than for Ischia. The imbalance is even larger at the global scale, with the Roma cumulative energy consumption being respectively around 4.5 time higher than for Napoli, 600 for Vico, 700 for Massa and 200 for Ischia. Roma energy demand is certainly affected by additional functions as the Capital of Italy, but the most likely source of energy consumption are lifestyles that are more expensive and exponential increase of energy consumption for the supply of resources from much larger areas. This partially applies to Napoli and translates into a global-to-local energy ratio (Tabble 1) higher than 4 for Roma and Napoli, and between 2 and 3 for the smaller urban systems. Of course, Table 1 does not include the renewable sources that are received outside of technology (e.g. solar energy driving evapotranspiration and photosynthesis), nor the ecosystem services supporting climate regulation, population wellbeing, material resource generation over time.

**Table 1.** Commercial energy expenditures of the investigated urban systems, at local and global scales (average values, 2010-2011).

| | Roma | Napoli | Vico Equense | Massa Lubrense | Ischia |
|---|---|---|---|---|---|
| **Local scale** | | | | | |
| $ton_{oil\ eq.}$/yr | 2.34E+06 | 6.23E+05 | 6.46E+03 | 7.44E+03 | 1.83E+04 |
| $kg_{oil\ eq.}$/inhabitant | 0.859 | 0.648 | 0.322 | 0.554 | 0.979 |
| $kg_{oil\ eq.}$/€ | 0.04 | 0.04 | 0.03 | 0.05 | 0.07 |
| $kg_{oil\ eq.}/m^2$ | 1.82 | 5.31 | 0.22 | 0.38 | 2.27 |
| **Global scale** | | | | | |
| $ton_{oil\ eq.}$/yr | 1.16E+7 | 2.54E+06 | 1.93E+04 | 1.65E+04 | 5.88E+04 |
| $ton_{oil\ eq.}$/inhabitant | 4.24 | 2.64 | 0.96 | 1.23 | 3.16 |
| $kg_{oil\ eq.}$/€ | 0.19 | 0.16 | 0.08 | 0.12 | 0.23 |
| $kg_{oil\ eq.}/m^2$ | 8.99 | 21.65 | 0.66 | 0.84 | 7.31 |
| **global/local energy ratio** | 4.94 | 4.08 | 2.98 | 2.22 | 3.22 |

*Assessing emergy inflows and their characteristics*

Table 2 lists the aggregated emergy flows supporting the investigated urban systems. The calculation procedure for such flows is shown in the Appendix Table A.1, dealing with the metabolism of Napoli, in the year 2011, while other examples can be found in the cited literature. All input data, originally expressed in units of energy (J), mass (g), or currency (€), are converted into their emergy equivalent (sej) by means of appropriate UEVs. Input flows are then aggregated into Locally Renewable (R), Locally nonrenewable (N), imported energy ($F_1$), imported food and water ($F_2$), other goods ($F_3$) and economic categories (Labor and Services, LS). The "Other goods" category mainly includes machinery, construction materials, metals, chemicals, wood, paper, etc. The economic categories include direct labor of commuters as well as the indirect labor performed outside the system boundary to process and delivers the imported input resources (services); local labor is not directly included because it is supported by local and imported resources already accounted for and therefore there would be a double counting procedure. Direct labor is accounted for as person-years applied, and converted to emergy by means of an average emergy per person factor ($sej/person*yr^{-1}$). Services (indirect labor) are accounted for as background labor inputs; due to the multiplicity of process steps in which labor was applied to the background supply chain, it is hardly accountable as hours or years, and therefore needs to be accounted for on a monetary basis, converting money paid for imports into emergy equivalents through an average emergy-to-GDP intensity factor of Italy (emergy intensity of currency, emergy/GDP ratio, sej/€) in a given year (Ulgiati and Brown, 2013). Table A.1 (and consequently Table 2) also provide an estimate of the fraction of LS that is supported by renewable resources and the fraction that should be considered nonrenewable in Italy, based on a country's emergy analysis, that we have performed for the year 2011 (updating Pereira et al., 2013). Moreover, the total emergy

U is calculated with and without including the emergy that supports LS, in order to ascertain to what extent the urban economy is directly supported by raw resources and to what extent it is driven by outside labor and services. It appears that LS accounts for between 25% and 40% of total emergy use in the different urban systems, with lowest % in Massa Lubrense (around 26%) and highest (around 40%) in Napoli and Ischia.

Disaggregating resource flows and labor flows helps to identify where a system can be improved for increased environmental sustainability.

**Table 2.** Emergy flows supporting the investigated urban systems (x 1E+18 sej/yr).

| Flow | **Roma** | **Napoli** | **Vico Equense** | **Massa Lubrense** | **Ischia** |
|---|---|---|---|---|---|
| **R** | 40.8 | 33.5 | 1.3 | 4.2 | 2.2 |
| **$LS_R$** | 967.0 | 302.0 | 3.0 | 1.7 | 8.7 |
| **N** | 11.8 | 0.1 | 0.1 | 0.3 | 0.01 |
| **$F_1$** | 14400.0 | 3890.0 | 45.7 | 51.5 | 128.0 |
| **$F_2$** | 8570.0 | 1470.0 | 6.1 | 4.1 | 25.0 |
| **$F_3$** | 16400.0 | 2610.0 | 62.2 | 21.3 | 52.4 |
| **$LS_N$** | 15200.0 | 4740.0 | 47.5 | 26.6 | 136.0 |
| **U** | 39500.0 | 8010.0 | 115.0 | 81.3 | 207.0 |
| **$U_{LS}$** | 55600.0 | 13000.0 | 166.0 | 110.0 | 352.0 |

Notes for Table 2: R stands for renewables, $LS_R$ for the renewable portion of labor and services, N for local non-renewables, $F_1$ for imported energy, $F_2$ for imported food and water, $F_3$ for other goods, $LS_N$ for the non-renewable portion of labor and services.

Imported goods ($F_3$) represent the largest emergy input, followed by the imported fuels and electricity ($F_1$), for Napoli, Vico Equense and Massa Lubrense, while instead it represents the second largest input flow for Ischia. Figure 4 provides a graphic view of the importance of each input category, given as percentage of the total emergy use in each system.

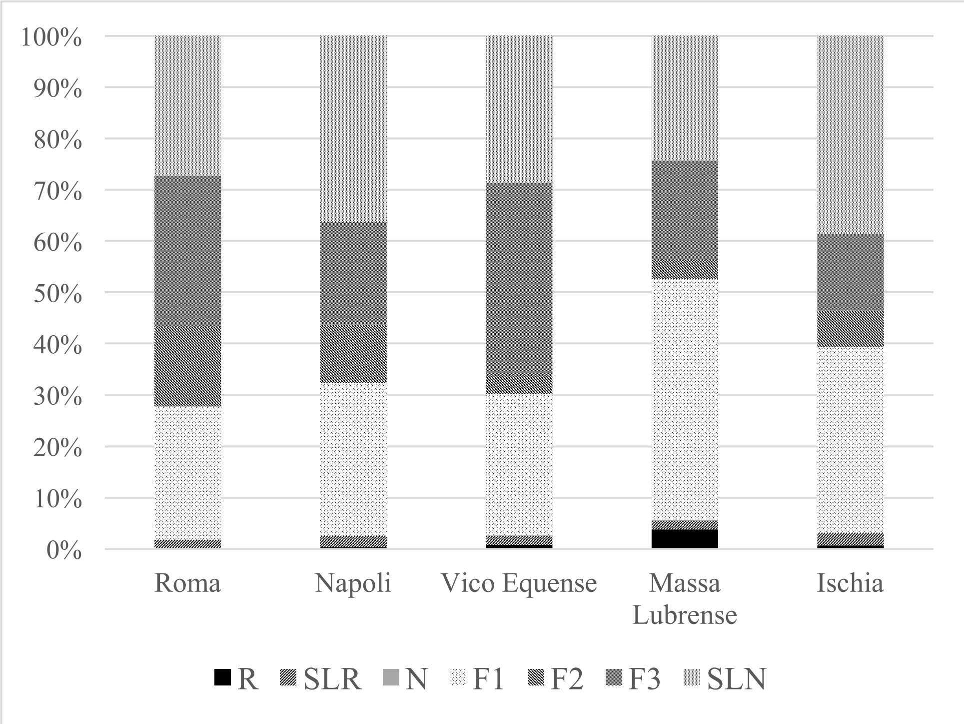


**Figure 4.** Relative importance of the emergy flows supporting each investigated system.

*Performance-oriented results*

A selection of the main emergy indicators, calculated also including the emergy of LS, is shown in Figures 5 and 6. The highest emergy intensity per person (an indicator of resource availability and potentially higher lifestyle) is shown by the city of Roma and the lowest by Massa Lubrense. Instead, the highest Currency Emergy Intensity (an inverse measure of system's efficiency in converting resources into monetary outcome) is shown by Ischia (suggesting its economy as very inefficient in GDP generation), while the lowest by Vico Equense. Napoli also shows the highest Empower density (a measure of spatial concentration and land as potentially limiting factor for future growth), while Massa the lowest. Finally, the more sustainable system, from the point of view of its balance of economic activities and environmental resources (ESI), seems to be Massa Lubrense, while Roma appears the less resource-sustainable.

The calculated values can be compared to the average values of Italy as a whole in the year 2011, shown in Table 3, with Roma and Ischia being above the average Italian values of Population emergy intensity, all urban systems being below the Italian Currency emergy intensity (except Ischia), and all systems showing an ESI much lower than the average Italian sustainability index, except Massa Lubrense. The Italian economy is 4% renewable, similar to Massa Lubrense, while all the other systems are much below 1%. Comparing urban systems to a national economy offers a benchmark, in that each of them should be organized in such a way as not to contribute to worsen the national performance indicators. Dedicating a buffer area by setting some land aside (Brown and Ulgiati, 2001) may be a theoretical solution, limited by land availability, in so calling for improvement in resource use within the urban systems, for lower environmental loading.

**Table 3** – Emergy indicators of Italy in the year 2011 (*)

| Indicator | Unit | Amount |
|---|---|---|
| Population emergy intensity | sej/person | 1.66E+16 |
| Currency emergy intensity | sej/€ | 1.02E+12 |
| Empower Density | sej/m$^2$ | 3.27E+12 |
| EYR | - | 1.37 |
| ELR | - | 24.46 |
| %REN | % | 4% |
| ESI | - | 0.056 |

(*) This study, after Pereira et al., 2013

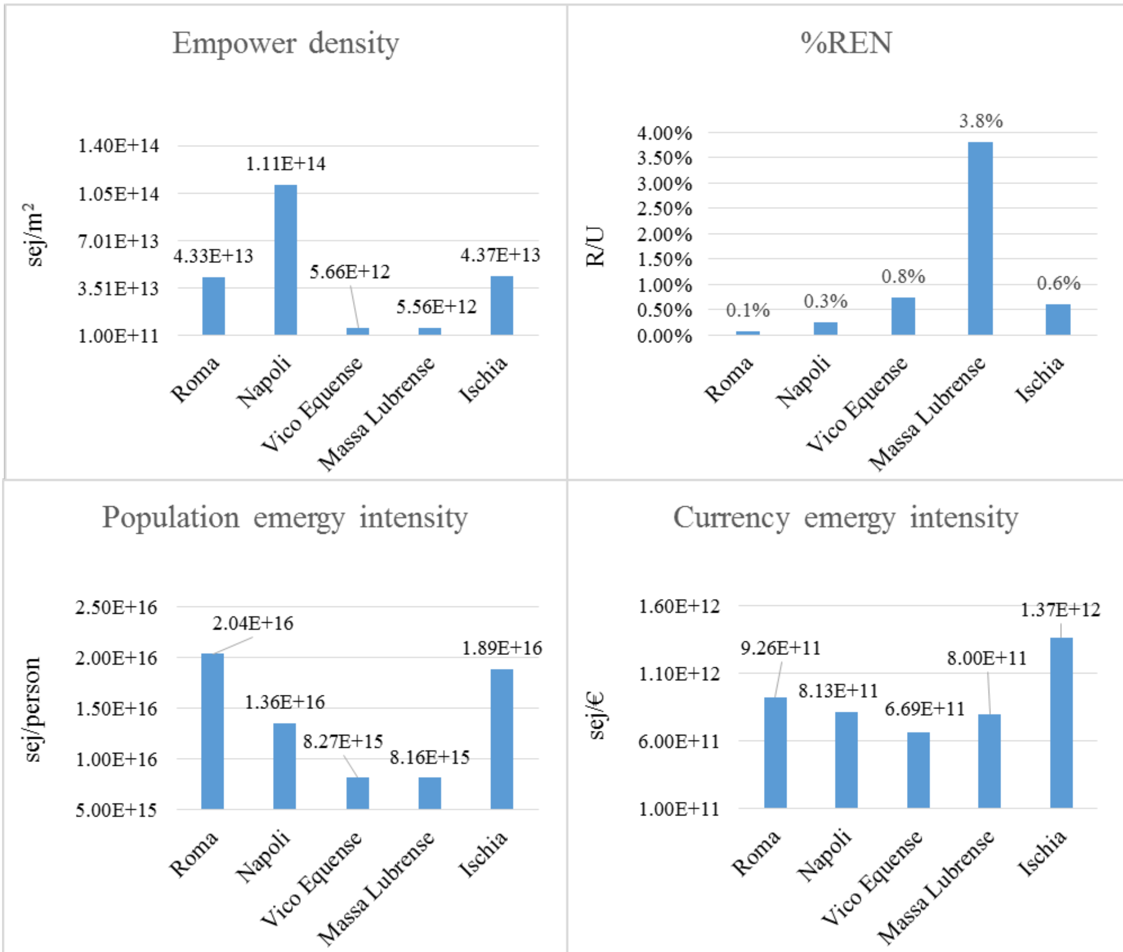


**Figure 5.** Calculated emergy intensities (sej/m$^2$; sej/person; sej/€) and renewable fraction (R/U) as percentage of the total emergy.

Of course, average emergy indicators hide a hierarchy of unequal access to and use of resources by different social classes, for which a more detailed assessment across space, age and income classes would be needed. However, these values provide a starting point to understand the main characteristics of the urban system, to compare cities from the point of view of their welfare development potential, and finally to create reference values to study the time evolution of the city dynamics depending on population and lifestyle trends.
All the calculated EYRs for the investigated cities have values close to one (Figure 6), indicating that these urban systems as expected – do not rely significantly on local resources, except to a very small extent, but support their economic and social processes mainly by means of imported resources. Their self-reliance is minimal, and their activities depend on ecosystem services available outside. Policies for increased reliance on local resources and good care of outside ecosystems are mandatory for survival of urban systems. The ESI, being a composite index, is affected both by the numerator (EYR, a measure of self-reliance) and by the denominator (ELR, a measure of distance from a fully renewable state). Consequently, ESI values of less than 1.0, as the ones computed in this study, are typically associated with unsustainable production and consumption processes, where lack of self-reliance is also coupled to a small level of renewability.

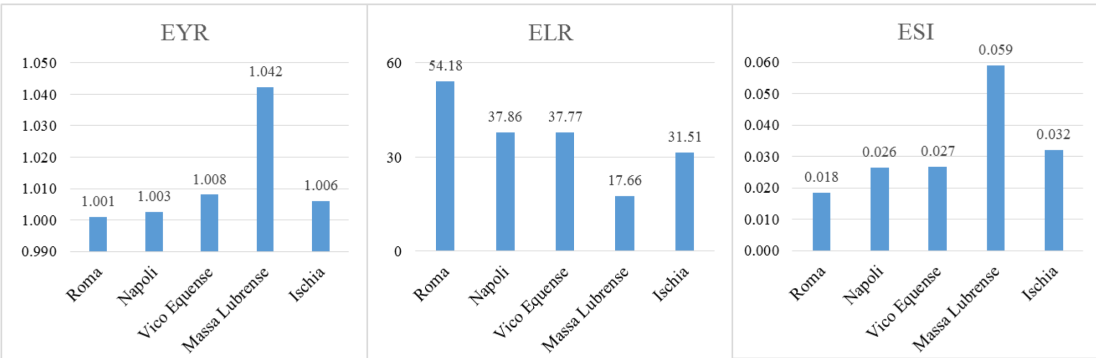


**Figure 6.** Calculated emergy indicators of the five investigated urban systems.

*Downstream-oriented results*

Results shown in Figures 5 and 6 look at the urban system under a “performance perspective”, i.e. the amount of resources needed to support selected functional units (one person, one €, one $m^2$) and the environmental quality of these resources (where they come from, their renewability, their generation time, etc.). Instead, Equation 7 links emissions to the areas potentially needed for their dilution, i.e. for the generation of ecosystem services suitable to achieve this purpose (above defined “downstream-oriented” perspective). Results are reported in Table 4. Two kinds of area are calculated, LCDA (Legal Concentration Dilution Area) and BCDA (Background Concentration Dilution Area), needed to generate enough environmental services (renewable emergy) for dilution of emissions, considering two different target “c” (legally acceptable or natural background concentration): the former, imposed by the

Italian regulation (Environmental law n. 152, 2006) and the latter being the ideal reference solution. Moreover, these "legal" and "background" areas are calculated with reference to both emissions released on local scale ($LCDA_1$ and $BCDA_1$, mainly from local combustion of fuels), and emissions released on a global scale ($LCDA_2$ and $BCDA_2$, also including emissions over the supply-chain of imported energy and materials). Further, the ratios between these calculated dilution areas and the actual city areas provide a measure of the distance of each urban system from the selected dilution target, through the definition of land amplification factors depending on the desired dilution: *Legal Concentration Amplification Factors* ($LCAF_1$ and $LCAF_2$) and *Background Concentration Amplification Factors* ($BCAF_1$ and $BCAF_2$). Non-$CO_2$ Emissions used in this study as well as legal and background concentrations of pollutants are indicated in the Appendix, Table A.2. The latter does not include $CO_2$ emissions, because of their different climate change mechanism, not affected by dilution (see below).
If the legal limits are considered, the additional areas needed are only relatively small additions to the actual city areas. The situation is very different if the target "c" is placed looking at the natural background condition, where reaching the ideal state of absolute sustainability requires an almost impossible land demand.
Table 4 shows that the dilution of local emissions down to the legally enforced limits ($LCDA_1$) would require to set aside relatively small areas, computed as fractions of city area (Amplification Factors). For example, it would be about 41% of the present area of Roma, 4% of the area of Napoli, etc. A similar dilution of the emissions all over the supply chain ($LCDA_2$) would require an additional area more or less equal to 115% of the present area of Roma, 24% for Napoli, while negligible fractions would be needed for the small urban systems of Massa Lubrense, Vico Equense, Ischia. However, as emissions released at global scale are actually released elsewhere, the area so calculated is a measure of the people footprint and could be located anywhere. Such land demand is reasonable and might be met by partially decreasing the emissions and partially increasing the natural area dedicated to parks and forests, no matter if close to the urban systems or elsewhere. The situation would be much more difficult if the goal is to abate the emissions back to the environmental background concentration. This would require dedicated set aside areas very larger than the actual urban areas. In the case or Roma, for example, $BCDA_1$ would require a buffer area about 38 times the urban area of Roma, while $BCDA_2$ would require an enormous 80 times! Although understandable, such a request is clearly impossible to meet and urgently calls for decreased emissions, if an absolute environmental sustainability is the goal.

A similar computation exercise was performed with $CO_2$ emissions calculating $CO_2$ amplification factors ($CO_2$ AF).
Uptaking the $CO_2$ released locally by the combustion of fossil fuels (Table 5) would require around 6 times the city area, in the case of Roma and Napoli, while between 4% and 34% of city area in the case of small systems. In a like manner, the uptake of

total $CO_2$ emissions all over the supply-chain would require proportionally much larger areas.

**Table 4.** Calculated additional area ($m^2$) needed to provide the ecosystem services (emergy) needed to dilute local and global emissions according to Italian regulation (Environmental law n. 152, 2006) and down to the natural background condition.

| | | Roma | Napoli | Vico Equense | Massa Lubrense | Ischia |
|---|---|---|---|---|---|---|
| Actual Area (AA) | $m^2$ | 1.29E+09 | 1.17E+08 | 2.93E+07 | 1.97E+07 | 8.05E+06 |
| **Dilution of local and global emissions according to legally enforced concentration** | | | | | | |
| $LCDA_1$ | $m^2$ | 5.23E+08 | 4.12E+06 | 8.22E+04 | 1.78E+04 | 2.89E+04 |
| $LCAF_1$ | $LCDA_1$/AA | **0.41** | **0.04** | **0.003** | **0.0009** | **0.004** |
| $LCDA_2$ | $m^2$ | 1.48E+09 | 2.80E+07 | 1.76E+05 | 2.38E+04 | 2.02E+05 |
| $LCAF_2$ | $LCDA_2$/AA | **1.15** | **0.24** | **0.01** | **0.0012** | **0.025** |
| **Dilution of local and global emissions down to background environmental concentration** | | | | | | |
| $BCDA_1$ | $m^2$ | 4.85E+10 | 3.82E+08 | 7.63E+06 | 1.65E+06 | 2.68E+06 |
| $BCAF_1$ | $BCDA_1$/AA | **37.76** | **3.26** | **0.26** | **0.08** | **0.33** |
| $BCDA_2$ | $m^2$ | 1.04E+11 | 1.29E+09 | 1.64E+07 | 2.21E+06 | 8.22E+06 |
| $BCAF_2$ | $BCDA_2$/AA | **80.69** | **11.00** | **0.56** | **0.11** | **1.02** |

Results from Table 5 are in the same order of magnitude as results from Table 4, which confirms the absolute need for reduction of emissions and, at the same time, setting aside enough buffer area for sustainable city development.

**Table 5** – Areas needed for uptake of local and global scale $CO_2$ emissions considering the mean value of NPP (400 g/$m^2$ of Carbon absorbed in one year) in the Mediterranean region (after Lieth, 1975).

| | Roma | Napoli | Vico Equense | Massa Lubrense | Ischia |
|---|---|---|---|---|---|
| $CO_2$ emissions at local scale (g/yr) | 1.31E+13 | 1.01E+12 | 1.65E+09 | 1.95E+09 | 4.05E+09 |
| Area to uptake local $CO_2$ emissions ($m^2$) | 8.93E+09 | 6.85E+08 | 1.12E+06 | 1.33E+06 | 2.76E+06 |
| $CO_2$ AF | **6.95** | **5.84** | **0.04** | **0.07** | **0.34** |
| $CO_2$ emissions at global scale (g/yr) | 5.07E+13 | 7.63E+12 | 5.65E+09 | 4.81E+09 | 1.78E+10 |
| Area to uptake global $CO_2$ emissions (m2) | 3.46E+10 | 5.20E+09 | 3.85E+06 | 3.28E+06 | 1.21E+07 |
| $CO_2$ AF | **26.89** | **44.34** | **0.13** | **0.17** | **1.50** |

*Upstream-oriented results*

Equations 7 to 11 provide an upstream perspective, summarized in Table 6. Instead of looking at the environmental services needed for dilution and abatement of emissions (downstream perspective), focus is now placed on the intensity of renewable and nonrenewable resource use for the process to occur in an environmentally sustainable way, namely on an acceptable balance of local, imported, renewable and nonrenewable sources. Table 6 reports the area needed to capture enough renewable energy to support the process by replacing nonrenewable; it also shows the previously defined amplification ratios between the calculated renewable support areas and the actual city areas, in so quantifying the Total Renewability Amplification Factor (TRAF), the Relative Loading Amplification Factor (RLAF), the Relative Sustainability Amplification Factor (RSAF), and the Absolute Sustainability Amplification Factor (ASAF). Consequantly, a support area is calculated under these four different assumptions. By comparison with the urban system area, an amplification factor can be derived, namely a measure of distance from a state consistent with the assumption. It is not surprising that the two "absolute" sustainability conditions (Assumptions 1 and 4) would require an enormous support land, while assumptions 2 and 3 concerning a "relative" sustainability yield a land demand in the same order of magnitude as needed for background dilution of emissions or total $CO_2$ uptake by photosynthesis.

**Table 6.** Emergy-based indicators measuring the set aside area ($m^2$) needed to generate ecosystem services in support of the desired level of sustainability.

| | | Roma | Napoli | Vico Equense | Massa Lubrense | Ischia |
|---|---|---|---|---|---|---|
| Actual Area (AA) | $m^2$ | 1.29E+09 | 1.17E+08 | 2.93E+07 | 1.97E+07 | 8.05E+06 |
| **Assumption 1: fully renewable support to the system (Equation 7)** | | | | | | |
| TRA | $m^2$ | 1.72E+12 | 4.46E+10 | 3.80E+09 | 4.90E+08 | 1.28E+09 |
| TRAF | TRA/AA | **1338** | **380** | **130** | **25** | **159** |
| **Assumption 2: $ELR_{system} \leq ELR_{country}$ (Equation 9)** | | | | | | |
| RLA | $m^2$ | 7.03E+10 | 1.82E+09 | 1.55E+08 | 2.00E+07 | 5.23E+07 |
| RLAF | RLA/AA | **54.7** | **15.5** | **5.3** | **1.02** | **6.5** |
| **Assumption 3: $ESI_{system} \geq ESI_{country}$ (Equation 10)** | | | | | | |
| RSA | $m^2$ | 6.56E+10 | 1.42E+09 | 1.39E+08 | 1.82E+07 | 3.85E+07 |
| RSAF | RSA/AA | **51.0** | **12.1** | **4.8** | **0.925** | **4.8** |
| **Assumption 4: $ESI_{system} = 10$ (selected as worldwide reference value, Equation 11)** | | | | | | |
| ASA | $m^2$ | 1.72E+13 | 4.43E+11 | 3.76E+10 | 4.69E+09 | 1.27E+10 |
| ASAF | ASA/AA | **13346** | **3781** | **1284** | **238** | **1575** |

Notes:

TRA= Total Renewability Area; TRAF= Total Renewability Amplification Factor

RLA= Relative Loading Area; RLAF= Relative Loading Amplification Factor

RSA= Relative Sustainability Area; RSAF= Relative Sustainability Amplification Factor

ASA= Absolute Sustainability Area; ASAF= Absolute Sustainability Amplification Factor.

*Discussion*

It is certainly crucial to carefully monitor the local and cumulative energy expenditures by cities as well as to realize that energy demand grows nonlinearly with urban systems' size (Table 1). Moreover, it is also very important to become aware of the fact that the cumulative large-scale emergy demand is 3-4 times higher than local energy use. This is an important starting point for planners of urban sustainability, in that a small achievement locally may have unexpected positive consequences globally. However, restricting management and policy decisions to a monodimensional assessment (how much energy, how much water are consumed; how much $CO_2$ is released), although useful, is partial and may be misleading. Individual assessments of specific flows can be more fruitfully linked into a network of flows, for comprehensive systems understanding and effective policies. The emergy overview provided in Table 2 and graphically depicted in Figure 4 provides the basis of a comparison of the main resource flows (not only energy or water) in comparable units, including renewables, economic flows, imported items, complementing energy and economic approaches.
As with all modern urban systems, direct environmental renewable flows (R) supporting the investigated cities are very small compared to the material flows of goods ($F_3$), fuels ($F_1$) as well as economic flows invested in support of the non-renewable fraction of labor and services ($SL_N$) (Table 2). The latter services are involved in the supply chain of goods and energy, but also and perhaps mainly in the implementation and maintenance of the related infrastructure (governmental services, security, health services and other social functions necessary for correct functioning of urban systems and supply chains). The opposite would be true if one investigates an ecosystem without humans, such as a forest or a lake, where direct environmental flows would be dominant (Ulgiati and Brown, 2009). Understanding which flows are the top contributors of the environmental support (i.e. which are the most important emergy flows) helps to identify the strength or fragility, the sustainability and the resilience of each urban system, according to the dependence on specific local or imported, renewable or nonrenewable resource flows. The sustainability assessment of a city must include an appropriate area, as a source of resources and a sink for its emissions. The issue is that there are many different ways to calculate this area, and that the area assigned to an urban system (or to any system as well) should not conflict with the areas needed in support to other systems. This is, in our opinion the real, and most often disregarded, constraint to the sustainability of production and consumption systems. Any system living beyond such constraints actually conflicts with the sustainability of "neighbors".

*The performance-oriented sustainability perspective*

A sustainability assessment may be performed under several different points of view. Figures 4, 5 and 6 support the so-called "performance perspective", i.e. the efficiency of resource use to support selected functional units and the environmental quality of these resources (where they come from, their renewability, their generation time, etc). These aspects are captured by showing the percentages of the different categories of resources needed (Figure 4), the percentage (very low) of renewable emergy supporting each urban system as well as the emergy intensities per unit of land (empower density), population (emergy per capita) and currency (emergy per Euro). Each "performance" indicator suggests an aspect of the system's behavior and calls for specific policies:

(a) The low renewable emergy percentages in all urban systems (much smaller than the Italian average, except for the urban system of Massa) urgently call for more sustainable use of resources. Since, in general, it is impossible to amplify the amount of renewables R (already fully included in the accounting), the %REN can only be increased by decreasing the fraction of nonrenewable emergy input (more efficient use of fuels, minerals, electricity, among others);

(b) All urban systems show empower densities higher than the average Italian value, confirming cities in a higher hierarchical and resource convergence position, than the surrounding landscape. The higher empower density of Napoli compared to Roma parallels its highest population density and suggests land as a limiting factor, in so calling for policies of guided and incentived population relocation towards increased wellbeing in less crowded areas;

(c) Only Roma and Ischia show higher values of emergy per capita than the average value for Italy in the same year (2011). The highest emergy intensity per capita in Roma, although not coupled to highest population and empower densities, suggests a potentially higher standard of living. Considering, however, Roma to be the Capital of Italy, a fraction of such higher emergy availability may be due to the multiplicity of functions the city must accomplish. Ischia likely benefits from very high tourism revenues per capita compared to the other urban systems.

(d) All the investigated urban systems (except Ischia, slightly above) show Currency Emergy Intensities (sometimes also named Emergy-to-Money Ratio, EMR) lower than the Italian average in the same year. Values suggest urban systems as slightly more efficient than the country as a whole in converting resources into monetary wealth (i.e. requiring less emergy per unit of GDP generated). This may be attributed to the presence of primary and secondary economies (agriculture, industry, infrastructure) at country level and instead the dominance of commerce and finance at city level, affecting the decoupling of resources (real wealth) and the monetary representation of wealth (GDP).

(e) The performance ratios (EYR, ELR and ESI) show better values at the Italian level, thanks to the supporting effect of less urbanized, agricultural and forested areas, while instead values indicate much lower sustainability at city level (except for Massa Lubrense, characterized by larger supporting area around): this suggests cities should always be evaluated together with their supporting area. The EYR for all cities is close to 1 indicating that no significant appropriation and benefit from local resources use takes place within the city boundaries compared to an overwhelming amount of imported nonrenewable sources. The city acts, in fact, as a resource conversion structure for generation of large amount of primary and manufactured resources into high quality information flows (culture, money).Large fractions of resources supporting cities are converted outside in so indicating their huge dependence from non-local sources and heavy load on the surrounding environment and far-away regions of the world. The ESI is very low for all systems, due to both low reliance on local resources and high environmental loading, calling for global de-growth policies, decreased outside imports and increased reliance on renewables (e.g. capture more renewable electricity from solar photovoltaic, in so decreasing the fossil electricity demand from the grid).

*The downstream-oriented sustainability perspective*

The different order of magnitude between the calculated LCDAs and BCDAs in Table 4 as well as the large areas for $CO_2$ uptake (Table 5), clearly demonstrate how available environmental services and related land might become limiting factors for human economies, if strict limitations to altering biosphere concentrations of pollutants are enforced. While legal enforced limits are not too difficult to meet in terms of set aside land, the dilution of emissions down to the biosphere background concentration or the uptake of all the $CO_2$ released by means of reforestation activities appear to be a mission impossible at the present land occupation by population and assets worldwide. Considering emissions at global scale cannot be solved through increasing support land because this land is simply not available. Solution calls for: (a) awareness of the actual global scale impact of our local use of a given resource; (b) the opportunities for improvement at global scale, driven by optimization of resource use at local scale; (c) the advantages of technological improvements that decrease material, energy and emergy intensities, and finally (d) the advantages of a better mix of input resources capable of generating lower global scale impacts. Sustainable consumption is an important factor determining energy use and energy efficiency in society. Choices of what and how to consume (where goods come from, how they are produced, how fast they are converted to waste, how and to what extent recycling patterns occur) and choices about growth in economies (qualitative versus quantitative growth) affect energy and material resource consumption patterns. Consumption determines upstream and indirect energy use in production activities. Understanding the indirect impacts of local consumption (households, private transportation, energy management, etc.) is crucial towards decreasing larger scale energy uses and resource depletion.

It appears evident that cities are very demanding in terms of environmental services, an evaluation only based on combustion-generated emissions, and the ecosystem service related to the air quality regulation is not complete. However, while in the previous calculation procedure we calculate the area needed to produce the important service of regulating air quality by diluting pollutants from the atmosphere, in other cases another ecosystem service could be more relevant to specific problems of the municipal management.

*The upstream-oriented sustainability perspective*

As a consequence of the above reasoning, an upstream-oriented solution seems more likely to be implemented than an "end-of-pipe" buffering. In particular, Assumptions 2 and 3 of Table 6 suggest the investigated system should not to contribute to an increase in the Environmental Loading Ratio of the country and should not decrease the overall sustainability of the country provide a "relative", not to strong constraint to production and consumption. The result of the calculated amplification factors was much larger than 1 in most cases, except for Massa Lubrense. More than 10% of the emergy supporting Massa Lubrense is from renewable driving forces and this makes the municipality the more environmentally sustainable. However, as demonstrated by Brown and Ulgiati (2011b), the sustainability index ESI can be very high as the result of either high values of R (and/or N), and very low values of F. Their Monte Carlo simulations show that ESI is maximized with three combinations of the inequality (R > N > F, N > R > F, R > F > N).

The "absolute sustainability" area (ASA, Table 6) computed taking as reference an ESI equal to 10 (considered as ideal performance worldwide), can be considered as a measure of absolute sustainability independent from the country's economy where the system is embedded. For this reason, ASA can be used to compare socio-economic systems from different countries measuring the distance of the investigated system from an ideal environmentally sustainable state.

Within the upstream-oriented perspective, a sensitivity scenario can be tested related to the city of Napoli. Let's assume that the following resource use changes are achieved:

50% fuels for transport (thanks to increased efficiency of engines, partial replacement of conventional vehicles with electric ones, increased use of mass transportation modalities, better organization of commuting needs);

50% fuels for heating (thanks to improved energy efficiency of buildings and heating devices; better materials; energy saving technologies);

+ 15% electricity consumption (for electric vehicles recharge) and 50% of conventional electricity replaced by electricity from photovoltaic.

- 50% materials for building sector (thanks to reuse, recycle and circular economy patterns in building and road construction).

If resource use changes are entered in Table A.1, Appendix, related to the emergy metabolism of Napoli, a number of changes in performance indicators can be calculated. Changes of emergy signature (a diagram showing the main input categories) are shown in Figure 7, with important changes in flows $F_1$, $F_3$, $LS_N$. Other efficiency and local savings options as well as changed energy and material mixes would translate into additional improvements. Since $LS_N$ is mainly linked to the category $F_2$ (food items), improvement in dietary patterns (less food waste, use of food produced at short distance) would also translate into a decrease of the emergy demand for Labor&Services.

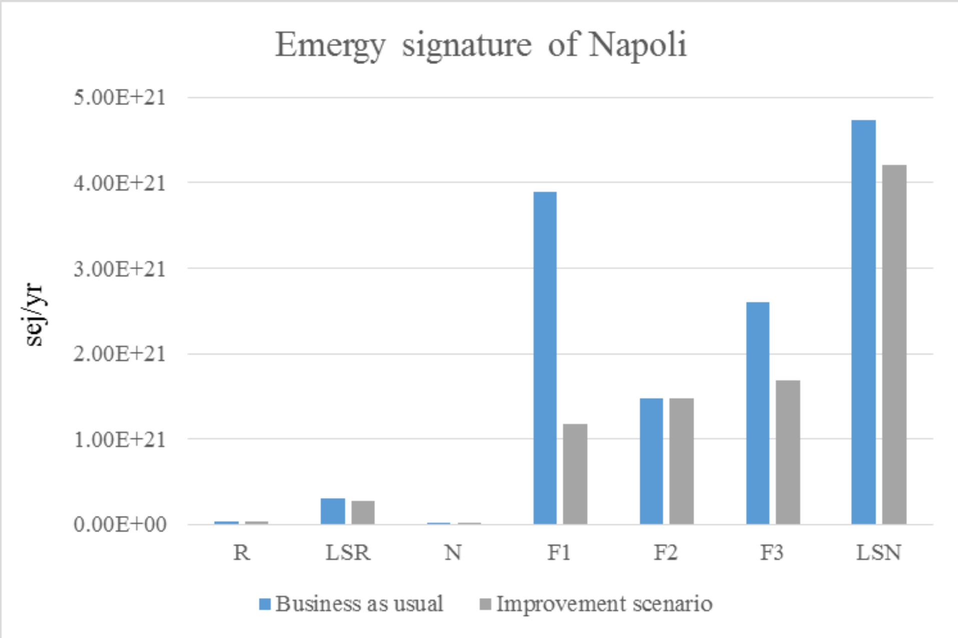


**Figure 7.** Change in the emergy signature.

The assumed changes in supporting flows would translate into changed performance indicators, as shown in Table 7, where Land Amplification demand decreases by 50% in most cases and improvement by at least 30% are achieved in all indicators, except EYR. Such improvement scenario can be considered a preliminary, although partial, answer to the need for decreased land demand related to the previously discussed performance-oriented, downstream-oriented and upstream-oriented perspectives. By decreasing emergy demand locally or globally, less buffer or support land is needed for a city sustainability.

**Table 7**. Improvement scenario for the city of Napoli (Italy)

| Indicator | Business as usual | Improvement scenario | change in percentage |
|---|---|---|---|
| Population emergy intensity | 1.36E+16 | 9.45E+15 | -30.4% |
| Currency emergy intensity | 8.13E+11 | 5.66E+11 | -30.4% |
| Empower density (sej/m$^2$) | 1.11E+14 | 7.74E+13 | -30.4% |
| EYR | 1.0026 | 1.0305 | +2.8% |
| ELR | 37.86 | 28.29 | -25.3% |
| ESI | 0.026 | 0.036 | +37.6% |
| LCAF1 | 0.04 | 0.02 | -50.0% |
| LCAF2 | 0.24 | 0.18 | -23.9% |
| BCAF1 | 3.26 | 1.63 | -50.0% |
| BCAF2 | 11.00 | 8.01 | -27.2% |
| RAF | 379.9 | 255.3 | -32.8% |
| RLAF | 15.5 | 10.4 | -32.8% |
| RSAF | 12.1 | 6.2 | -49.2% |
| ASAF | 3780.6 | 2535.4 | -32.9% |

*Conclusions*

The study explores the environmental sustainability conditions of five urban systems of different size in Italy, by means of CED, Cumulative Energy Demand, and EMA, Emergy Accounting. Both methods provided a measure of the dependence of cities on fossil energy and material resources, ecosystems services and human labor. The applied methods provide measures of both the extent and intensity of resource use, highlighting the advantages from policies promoting resource use efficiency and savings. The study also quantifies the environmental load generated by increased levels of consumption. A number of constraints linked to emissions (dilution levels criteria), to $CO_2$ uptake, to increased use of renewable resources, to an appropriate mix of local and imported, renewable and non-renewable inflows, and finally to relative and absolute sustainability conditions, were translated into computed emergy-based land demand. Finally, a number of policy options derived from performance indicators were explored.

In this perspective, in order to reach an increased level of sustainability of the investigated urban systems, several solutions can be suggested capable to decrease the use of imported and nonrenewable resources, among which:

- increase recycling and reuse (if waste cannot be upstream avoided);
- promote renewable energy sources (solar, geothermal, wind, among others) to replace fossils;
- increase efficient use of resources (e.g., prioritize public transport versus private);
- recover and, if possible, increase agricultural and urban green areas for local production.

The study confirms that cities cannot be sustainable organisms, given their dependence on imported resources. However, if local consumption is optimized also looking at the entire supply chain of resources, and if a suitable supporting land is set aside for generation of ecosystem services needed by the urban system, emergy-based sustainability indicators show that urban system's performances can be improved and that an equilibrium between the city and its surrounding environment can be established.

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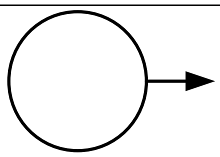
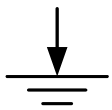
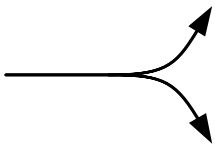
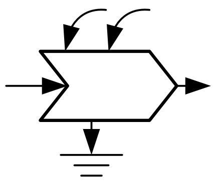
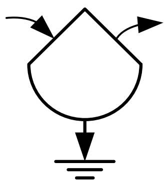
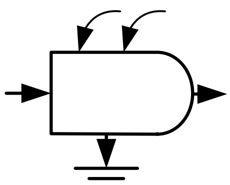
## APPENDIX

**Key for symbols (from Odum, 1996).**

| | |
|---|---|
|  | System Frame:<br>A rectangular box is drawn to represent the boundaries that are selected. |
|  | Source:<br>Any input that crosses the boundary is a source, including pure energy flows, materials, information, genes, services and inputs that are destructive. |
|  | Pathway Line:<br>Any flow is represented by a line, including pure energy, materials and information. Money is shown with dashed lines. |
|  | Heat sink:<br>This symbol represents the dispersal of available energy (potential energy) into a degraded, used state, not capable of further work. |
|  | Split:<br>A pathway that branches represents a split of flow into two of the same type. |
|  | Interaction:<br>Two or more flows that are different and both requires for a process are connected to an "interaction" symbol. The output of an interaction is an output of an production process, a flow of product. |
|  | Storage tank: Any quantity stored within the system is given a "tank" symbol, including materials, pure energy, money, assets, information, image and quantities that are harmful to others. Every flow in or out of a tank must be the same type of flow and mesured in the same units. |
|  | Producers:<br>"Producer" symbols are used for units on the left side of the systems diagram that receive commodities and other inputs of different types interacting to generate products. |

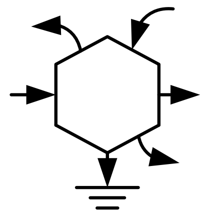
| | |
|---|---|
|  | Consumers:<br>"Consumer" symbols are used for units on the right side of the system diagram that receive products and feedback services and materials. |

**Table A.1 Emergy assessment of the City of Napoli in the year 2011.**

| | Item | Unit | Raw | UEV (sej/unit) | Emergy (sej/yr) | % |
|---|---|---|---|---|---|---|
| **Renewable Input (locally available)** | | | | | | |
| 1 | Solar radiation | J/yr | 3.26E+18 | 1.00E+00 | 3.26E+18 | - |
| 2 | Tide | J/yr | 1.48E+14 | 3.09E+04 | 4.59E+18 | - |
| 3 | Geothermal heat | J/yr | 1.29E+14 | 4.90E+03 | 6.32E+17 | - |
| | | | | *Sum of the primary flows* | *8.48E+18* | - |
| 4 | Wind | J/yr | 1.11E+15 | 1.00E+03 | 1.11E+18 | - |
| 5 | Rain (chemical potential energy) | J/yr | 6.89E+14 | 7.01E+03 | 4.83E+18 | - |
| 6 | Rain (geopotential energy) | J/yr | 1.17E+13 | 1.28E+04 | 1.50E+17 | - |
| 7 | Waves | J/yr | 7.76E+15 | 4.31E+03 | 3.35E+19 | - |
| | *Largest of the secondary and tertiary flows* | | | | *3.35E+19* | - |
| | | | | **Renewable flows** | **3.35E+19** | 0.3% |
| **Nonrenewable Input (locally available)** | | | | | | |
| 8 | Organic carbon in topsoil lost | kg/yr | 4.50E+05 | 1.84E+11 | 8.28E+16 | 0.001% |
| **Imported Input** | | | | | | |
| 9 | Gasoline | J/yr | 3.40E+15 | 1.48E+05 | 5.01E+20 | 3.8% |
| 10 | Diesel fuel | J/yr | 1.50E+15 | 1.43E+05 | 2.14E+20 | 1.6% |
| 11 | LPG (Liquid Petroleum Gas) | J/yr | 1.49E+14 | 1.41E+05 | 2.10E+19 | 0.2% |
| 12 | Heavy oil for domestic heating | J/yr | 1.59E+15 | 1.43E+05 | 2.27E+20 | 1.7% |
| 13 | Natural gas | J/yr | 9.30E+15 | 1.41E+05 | 1.31E+21 | 10.0% |
| 14 | Electricity | J/yr | 7.60E+15 | 2.13E+05 | 1.62E+21 | 12.4% |
| 15 | Water (from acqueduct) | $m^3$/yr | 5.62E+07 | 1.00E+11 | 5.62E+18 | 0.04% |
| 16 | Main Food Items | | | | | |
| *16a* | *Fish* | g/yr | 2.00E+10 | 1.02E+08 | 2.03E+18 | 0.02% |
| *16b* | *Meat* | g/yr | 6.89E+10 | 1.00E+10 | 6.89E+20 | 5.3% |
| *16c* | *Fruits and Vegetables* | g/yr | 1.69E+11 | 3.90E+08 | 6.57E+19 | 0.5% |
| *16d* | *Milk, cheese and other derivatives* | g/yr | 8.22E+10 | 8.00E+09 | 6.57E+20 | 5.0% |
| *16e* | *Cereals and derivatives* | g/yr | 1.48E+11 | 3.30E+08 | 4.88E+19 | 0.4% |
| *16f* | *Wine and alcoholics* | g/yr | 5.20E+07 | 1.06E+09 | 5.53E+16 | 0.0004% |
| *16g* | *Olive and seed oils* | g/yr | 1.63E+07 | 3.21E+11 | 5.23E+18 | 0.04% |
| 17 | Steel and iron | g/yr | 4.19E+11 | 2.65E+09 | 1.11E+21 | 8.5% |
| 18 | Copper | g/yr | 2.69E+09 | 5.87E+08 | 1.58E+18 | 0.01% |
| 19 | Aluminium | g/yr | 2.40E+10 | 4.08E+07 | 9.80E+17 | 0.01% |
| 20 | Cement (Portland) | g/yr | 5.32E+11 | 1.25E+09 | 6.64E+20 | 5.1% |
| 21 | Rocks and Sediments for building sector | g/yr | 2.90E+12 | 1.56E+06 | 4.52E+18 | 0.03% |
| 22 | Glass | g/yr | 6.49E+10 | 2.50E+09 | 1.63E+20 | 1.2% |
| 23 | Plastics | g/yr | 1.45E+11 | 2.39E+09 | 3.48E+20 | 2.7% |
| 24 | Asphalt | g/yr | 3.36E+10 | 2.39E+09 | 8.04E+19 | 0.6% |
| 25 | Chemicals | g/yr | 3.27E+10 | 2.10E+07 | 6.85E+17 | 0.01% |

| | | | | | | |
|---|---|---|---|---|---|---|
| 26 | Wood | g/yr | 2.10E+08 | 7.32E+09 | 1.53E+18 | 0.01% |
| 27 | Textiles | g/yr | 1.42E+10 | 7.23E+09 | 1.03E+20 | 0.8% |
| 28 | Paper and derivatives | g/yr | 1.86E+11 | 4.82E+08 | 8.99E+19 | 0.7% |
| 29 | Fertilizers | g/yr | 2.04E+08 | 1.01E+11 | 2.06E+19 | 0.2% |
| 30 | Electric equipment | g/yr | 1.30E+09 | 4.95E+09 | 6.43E+18 | 0.0% |
| 31 | Machinery | g/yr | 1.45E+09 | 1.05E+10 | 1.52E+19 | 0.1% |
| 32 | Labor | unit | 1.25E+04 | 4.35E+16 | 5.44E+20 | - |
| | | | | *Labor (renewable fraction) 6%* | *3.27E+19* | 0.3% |
| | | | | *Labor (nonrenewable fraction) 94%* | *5.12E+20* | 3.9% |
| 33 | Services | €/yr | 2.70E+09 | 1.66E+12 | 4.49E+21 | - |
| | | | | *Services (renewable fraction) 6%* | *2.70E+20* | 2.1% |
| | | | | *Services (nonrenewable fraction) 94%* | *4.23E+21* | 32.4% |
| Total emergy (U) | | | | | **8.01E+21** | - |
| Total emergy with Labor and Services (ULS) | | | | | **1.30E+22** | 100.0% |

**Table A.2 Airborne pollutant concentrations according to national legally enforced as well as environmental background limits.**

| c (g/dm$^3$) | Enforced legal concentration (*) | Background concentration (**) |
|---|---|---|
| $NO_2$ | 4.00E-08 | 4.31E-10 |
| $SO_2$ | 2.00E-08 | 4.92E-10 |
| Particulate | 1.00E-08 | 3.00E-09 |

Note:

(*) Legal concentrations according to Italian Environmental law n. 152, 2006.

(**) $NO_2$ and $SO_2$ background concentrations according to Harte (1988); Particulate background concentration according to EEA (2012).

# CHAPTER 10.b Monitoring trends of urban development and environmental impact of Beijing, 1999–2006

## *Introduction*

The high rates of environmental change and accelerated species loss in the urban development process should be quantified to rebalance the social and environmental dimensions of sustainability. In this study, a matter, energy and emergy-based environmental impact assessment model is designed according to the framework of the Eco-Indicator 99 for monitoring the negative effects on human well-being and ecosystem integrity in the urban development system of Beijing from 1999 to 2006. The environmental impact assessment model is based on the sustainability promotion perspective, and emphasizes the determinants of human health and ecosystem integrity in the urban development process. It is vital that the links among human health, ecosystem integrity and urban sustainability are therefore considered especially from the perspective of a supply-side environmental cost evaluation (including ecological service supply, ecological and economic losses and investment for treatment). Results suggest that:

(1) out of all the pollutants, ecological services were mainly used to dilute sulfur dioxide and NH3–N;

(2) nitrogen dioxide and greenhouse gases released by the urban system contribute heavily to both ecological and economic losses evaluated in emergy terms; and (3) emissions impact, mainly from airborne pollutants, with small contribution from waterborne emissions, generally increases from 1999 to 2006, undermining the sustainability of Beijing. The emergy synthesis proves to be very appropriate to account for large-scale and indirect costs generated by pollution as side effects of economic activity. Such knowledge is a necessary pre-requisite to perform a reliable cost–benefit evaluation of urban sustainability strategies, and provide guidance for policy decision making to maximize benefits and minimize negative impacts.

## *Coupling technological progress, welfare and environmental care*

Evidence in recent decades of escalating human impacts on the ecological system worldwide raises concerns about the spatial and temporal consequences of negative effects on human well-being and ecosystem integrity (Sachs, 2005). Especially in the urban socioeconomic system, which has a distinctive pattern mix of the “internal” and “external” factors involved under the support of certain inner organization and limitation of the physical environment (Brown and Ulgiati, 2005), the fastest economic development is planned, coinciding with high rates of environmental change and accelerated species loss (Glasson et al., 2005). A number of ‘new’ potential health threats have been researched in recent years. Concern has been expressed over the environmental and health risks associated with the urban land use (Anilkumar et al., 2010), impact of urban sewerage system (Kolahi et al., 2009), effects of climate change and consequences to human health of ecological deterioration (Huntingford et al., 2007; Hayhoe et al., 2010). These interactions have caused the trepidation concerned the disruption in the balance of humanity and nature. Environment impact assessment is widely used to improve knowledge about the potential impact of a policy, inform decision-makers and affected people, and facilitate adjustment of the proposed policy in order to mitigate the negative and maximize the positive impacts. It can inform policy and decision making to maximize benefits and minimize negative impacts on urban sustainability strategies. However, current perspective of urban environmental impact analysis ignores the interdependence of human health and the integrity of the natural environment, as well as the complex social, economic, and health effects of environmental management decisions (Bhatia and Wernham, 2008). In order to rebalance the social and environmental dimensions of sustainability with the economic one, the socio-environmental damages of the urban system must be quantified. Over the past 20 years, there have been many studies focusing on the basic urban development process related to the input side and the environmental impacts (Wolman, 1965; Ayers and Kneese, 1969; Fischer-Kowalski, 1998; Fischer-Kowalski and Huttler, 1998; Daniels and Moore, 2002; Haberl, 2006; Harris et al., 2009). However, most of them are focused on urban industrial material production, such as those of Taiwan (Huang, 1998), Toronto (Sahely et al., 2003), Nantong (Duan, 2004), Sydney (Lenzen et al., 2004) and Paris (Barles, 2007).There are few studies focusing on household consuming process (Newman et al., 1996; Forkes, 2007; Dong and Wang, 2009) and even fewer dealing with the associated health burdens to the people and the surrounding ecosystem. Monetary measures are commonly used to assess the natural capital and human capital values and losses. The quantitative measure of urban development must be taken into proper account during both production and consumption processes. As a consequence, there is an urgent need to develop a quantitative methodology that can evaluate the adverse environmental effects of both production and consumption activities, addressing specific damages to human health and ecosystems, and taking into account how they affect the urban system's dynamics and sustainability.

*An integrated monitoring metrics for urban development and environmental impact*

The economic estimates of health and non-health damages are based on certain methodological tools or amalgamations and are as credible as these tools are. Valuation of health effects is a critical component in assessing the social costs of pollution: it allows the performance of cost–benefit analysis of pollution control measures and provides a basis for setting priorities for actions. Several methods or amalgamations have been applied in recent years, such as economic evaluation (Murray et al., 1994; Goedkoop and Spriensma, 2000; Ko et al., 2004), emergy analysis (Geber and Björklund, 2002; Brown and Ulgiati, 2005; Zhang et al., 2009a, 2009b, 2009c) and ecological cumulative exergy consumption analysis (Hau and Bakshi, 2004; Urban et al., 2010). All these studies focused on specific unhealthy impact in a certain process or sector of the total urban development process, and fewer researches concentrate on its comprehensive performance linking such impacts to a supply-side environmental cost evaluation (including ecological service supply, ecological and economic losses and investment for treatment).

Emergy synthesis is a useful method for environmental accounting derived from energy system theory that uses the energy (in units of the same kind) required to produce a good or service as a nonmonetary measure of the value or worth of components or processes within ecosystems and the economy (Odum, 1996). Till now, a large number of systems have been evaluated by means of the emergy method on regional scales and industrial sectors (Brown and Odum, 1992; Huang and Odum, 1991; Lan and Odum, 2004; Ulgiati et al., 2007; Lu and Campbell, 2009; Liu et al., 2009a; Ren et al., 2010; Lu et al., 2010). Dong and Wang (2009) structured a combining approach of emergy analysis and life cycle assessment to quantitatively investigate the live quality and negative impacts of metabolic process of the sub-urban residential area in Beijing. More researchers considered Beijing as a whole to evaluate the developing status of Beijing's environment and economic development and compared the results with those of other cities (Zhang et al., 2009a, 2009b, 2009c; Jiang et al., 2009; Zhang et al., 2009a, 2009b, 2009c). These studies developed related evaluation indicators based on the concept of “ecological cost” and “ecological wealth” (Ji, 2010).

However, these indicators were always used to sketchout the impact of emissions as a consequence that comes into existence or an extraneous to the socio-economic system itself. At this point we should find a way to “internalize” the types of “externalities”, and put emphasis on the impact of emissions on ecosystem and human integrity by transferring these losses to the system accounting. This is especially useful in regional environmental protection and regional policy decision making. Important headway has been made by some authors. Ulgiati et al. (1995) first pointed out that the impact of emissions on natural and human-dominated ecosystems requires additional emergy investment to take care of the damage or altered dynamics and to make a system or process sustainable. Ulgiati and Brown (2002) calculated the additional emergy for the environmental services required to dilute emissions, without considering atmospheric diffusion and chemistry. Hau and Bakshi (2004) first proposed the use of disability adjusted life years (DALYs) from Eco-Indicator 99 impact assessment method (E.I. 99) to evaluate the emissions' impact on human health of economic sectors by using ecological cumulative exergy consumption (ECEC) analysis. Brown and Ulgiati (2005) used the emergy method to suggest a system view to ecosystem's integrity and also to assess the emergy investment needed to restore ecosystem health. Lei and Wang (2008) tracked the waste treatment processes and calculated the transformities of the fly ash and slag in Macao, as a result of the incineration of municipal solid waste. Zhang et al. (2009a, 2009b, 2009c) integrated dilution and Eco-Indicator 99 methods to evaluate the sustainability of Chinese steel production. The research on a single industry was proposed by these authors as an initial case of application on regional scale. Therefore, considering cities as a multi-industry integrated system, emergy-based city studies should investigate the global impacts of emissions and convert them into a set of existing emergy indicators in order to provide suitable and scientifically based information for cost-effective abatement strategies and policy decisions. In seeking an effective model in the analysis of emissions, other authors developed hybrid LCA-based methodologies (Udo de Haes and Lindeijer, 2001), where emissions are characterized by end-point impact factors related to human and ecosystems health.

Our objectives in this study are threefold. First, we integrate upstream and downstream evaluation methods to quantify the environmental impact by addressing specific damages to human health and ecosystem's integrity and linking such impacts to a supply-side environmental cost evaluation. Second, we propose an evaluation model focused on urban development (both urban production and consumption activities). Finally, comparison of performances based on time series sheds light on the overall trend and provides an initial diagnosis of the urban development. The results of our study will enable urban policy planners to understand the interlinkage between production and consumption processes and their impact on human and natural capital.

As a continuation of our earlier effort of unified analysis based on emergy for evaluating the environmental and economic development in Beijing (Zhang et al., 2009a, 2009b, 2009c; Jiang et al., 2009; Liu et al., 2009b), this work serves as a further attempt to assess both the impact of emissions on ecosystem and human integrity and the energy resource consumption based on emergy analysis in a unitary way. The emergy values of human-made and natural capital lost were regarded as indirect inputs of ecological services for airborne and waterborne pollutants dilution and damage repair or replacement to "internalize" the "externalities" with emphasis on a joint application of the emergy synthesis and environmental pollutant impact assessment methods.

*Characteristics of the environment and economy in Beijing*

Beijing lies between longitudes 115°25′E and 117°30′E and between latitudes 39°26′N and 41°03′N (Fig. 1) in North China. Specifically, Beijing is located at the eastern edge of the Eurasian continent and belongs to the Bohai sea rim economic circle, with small plain in the south and mountains in the west and north, covering an area of 16,807.8 km2. The city's climate is a monsoon-influenced humid continental climate. In 2006, the total precipitation was 318 mm and the majority of it occurred in the summer.

Characterized by its long history and central political and cultural position, Beijing is amongst the most developed cities in China with a fully integrated industrial structure, including electronics, machinery, chemicals, light industry, textile and automobile manufacturing. The development of Beijing continues to proceed at a rapid pace, and by the end of 2006, Beijing's GDP was 0.79 trillion RMB, a year-on-year growth of 10.1% from the previous year. Like the other metropolises in developing countries, Beijing faces the dilemma of urban economic development versus social and ecological problems comprising the large floating population, high-yield agricultural land lost, resources shortage, high levels of pollution, ecological deterioration, and increasing disaster risk. This city is known for its smog, the quality of the water supply and the cost of the basic services such as electricity and natural gas. With renovations for the 2008 Olympics, Beijing has adopted a strategy of increasing government investments in pollution treatment and infrastructure construction. As a consequence, Beijing calls for urgent policy measures based on quantitative and comprehensive cost–benefit evaluation of urban sustainability strategies.

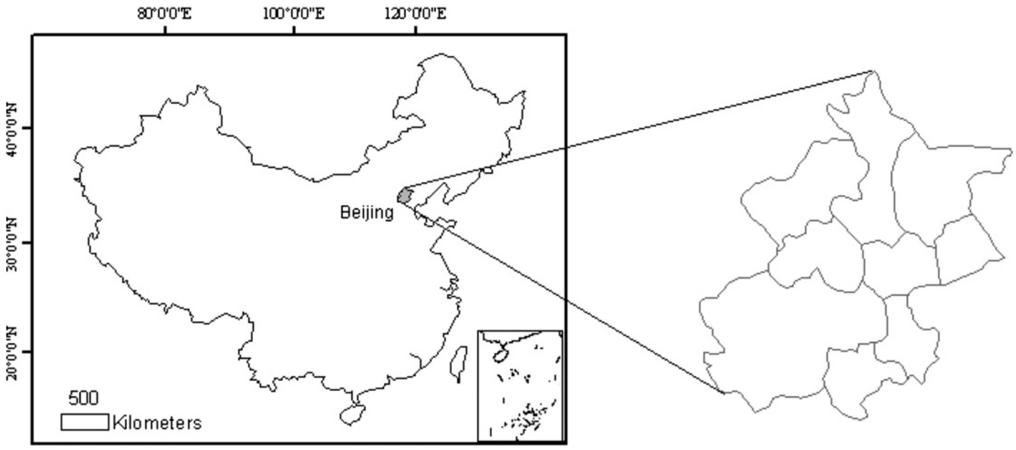



Fig. 1. Location of Beijing.

*Methods*

Every economic process generates useful products and undesired impacts at the same time (to the ecosystem, to human health, to human assets). Ulgiati et al. (1995) probed into the emergy resources required in order to prevent or fix reversible damages, and pointed out that

(1) additional emergy resources are needed to replace the lost assets or units, when irreversible damages occur, and that (2) when replacement is not possible, at least a conservative estimate of the natural or human capital loss should be attempted, based on the resources previously invested for its generation, in order to ascertain the true cost of a process product. Following Ulgiati et al. (1995) and Ulgiati and Brown (2002), additional emergy cost terms should be included in order to account for (a) dilution and abatement of emissions by natural processes, (b) abatement, uptake and recycle of emissions by means of technological devices, (c) repair of damages to human-made assets by means of maintenance activities, (d) reversible and irreversible damages to natural capital (e.g.: loss of biodiversity), and finally

(e) reversible and irreversible damages to human health. As a consequence, the total emergy cost U (here, U = used) can be calculated as:

$$U = R + N + F + F_1 + \ldots + F_n \qquad \text{Eqn. 1}$$

where R and N are respectively the locally renewable and nonrenew-able emergy resources, F is the emergy of imported goods and commodities (including their associated services) and where the $F_i$ terms include the environmental or human-driven emergy investments (here, F = feedback) needed to prevent or fix the damages occurred and charged to the process: $F_1 = \Sigma j\ F_{1,j}$ = the sum of all j-th input flows to prevent or fix damage 1; $Fn = \Sigma_k F_{n,k}$ = the sum of all k-th input flows to prevent or fix the n-th damage.

For the sake of clarity, if combustion emissions damage the facades of urban buildings, such a damage can be assessed in terms of the emergy investment Fi needed to restore it, i.e. $F_i = A \times \Sigma_k F_{n,k}$, where A is the damaged surface and $F_{n,k}$ are the emergy investments per unit surface (chemicals, paints, labor) needed to restore the facade disregarding the additional resource investments due to impact prevention or repair would underestimate the real demand for the process to occur and be sustainable.

The aim of this paper is to apply such a framework to the sustainable development and management of an urban system, taking the city of Beijing (China) as a case study. Such a goal requires that specific procedures should be identified and applied in order to calculate the additional resources needed for sustainable development of the urban system by removing those factors that affect human and environmental health.

*Emergy-based environmental impact assessment model*

Fig. 2 shows two patterns for release of emissions without (a) and with (b) waste treatment systems. It represents only a sub-system of the whole Beijing urban system which shows in Fig. 3, i.e. the waste released and its interaction with the urban system itself.

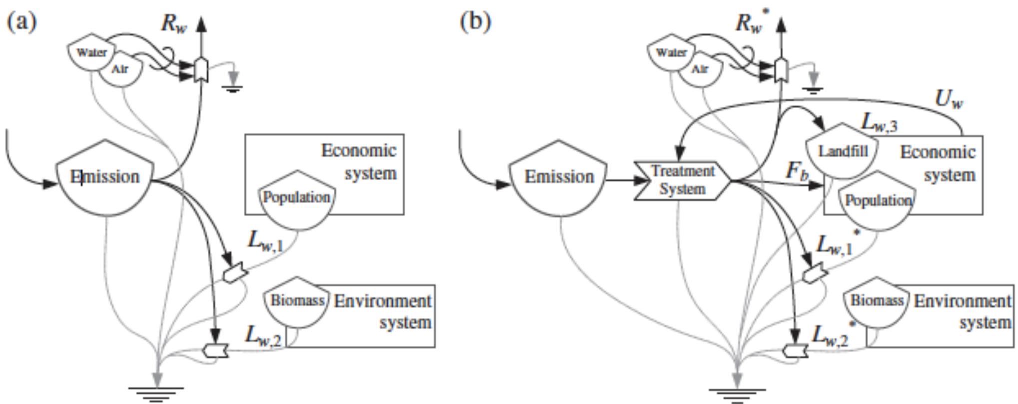



Fig. 2. Direct and indirect emergy inflows from environment and economic system (a) without and (b) with waste treatment system. $R_w$: emergy of ecological services needed to dissipate the emissions; $R^*_w$: emergy of ecological services needed to dissipate the emissions after treatment; $L_{w,1}$: emergy of the human health losses caused by the emissions; $L_{w,1}$: emergy of the human capital losses caused by the emissions after treatment; $L_{w,2}$: emergy of the natural capital losses due to the emissions; $L^*_{w,2}$: emergy of the natural capital losses due to the emissions after treatment; $L_{w,3}$: emergy of the human capital losses caused by land occupation; $U_w$: emergy of waste treatment input; $F_b$: emergy of feedback of useful products to the upstream process.

Air and water emissions and solid waste are controlled based on additional input of fuels, goods and labor force. The terms F1, …, Fn in Eq. (1) are indicated in Fig. 2 as $L_{w,n}$ in order to specifically point out their nature of emergy losses (L) associated to a process waste (w) generation. Without treatment, the emergy loss associated with damaged human capital is indicated as $L_{w,1}$, which means that some emissions cause pathological impacts to human beings that in turn require additional investment for replacement or fixing; meanwhile, other kinds of emissions, such as acid rain and lake eutrophication, may lead to loss of flora and fauna. The emergy loss associated with the degradation of natural capital is indicated as $L_{w,2}$. Untreated emissions need ecological services to render them harmless, such as dilution and abatement, and these emergies are indicated as $R_w$. In order to prevent or minimize further pollution damage, a waste treatment system can be applied as designed in Fig. 2(b). The waste treatment system could effectively reduce waste (not to zero) through additional resources input. The new (lower) human and natural capital emergy losses after waste treatment are denoted as $L^*_{w,1}$ and $L^*_{w,2}$ (being respectively $L^*_{w,1} < L_{w,1}$; $L^*_{w,2} < L_{w,2}$). Furthermore, the damage associated with solid waste disposal can be measured by land occupation and degradation, the emergy of which (i.e. the emergy value of land, irreversibly degraded) is denoted as $L_{w,3}$ (Cherubini et al., 2009). The additional emergy investment for treatment is denoted as Uw, and should be in principle lower than the damage-related losses $L_{w,n}$, in order to be feasible and rewarding. The waste treatment system is designed to recycle and reuse part of the emissions (flow $F_b$) through the use of eco-technologies. Such a recycle flow should allowa proportional decrease of the total emergy cost U, by decreasing the use of local nonrenewable resources N or by decreasing the imports F in Eq. (1). However, this improvementwas not accounted for in the present study, because the proposed pattern is not yet fully implemented in Beijing urban waste management policy.

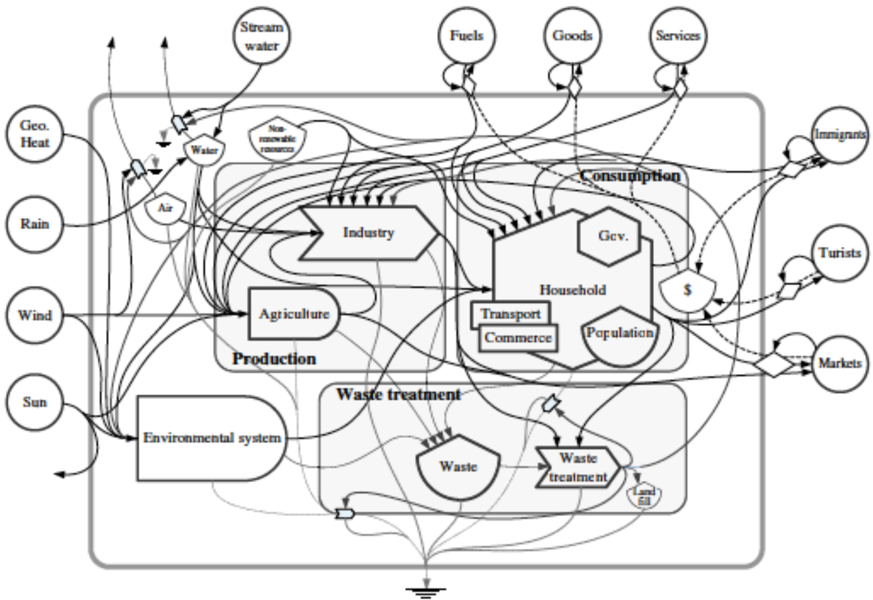



Fig. 3. Emergy flow system diagram of a typical urban socio-economic system.

*Evaluating the impacts of emissions*

*Quantifying ecological services*

Emissions are sometimes rendered harmless due to services provided by the ecosystem that dilute or abate the emissions to an acceptable concentration or state. The emergy value of these ecological services may be calculated from knowledge of the concentration and nature of the emissions, and the transformity of the relevant ecological services. For example, the emergy required to dilute nitrogen dioxide in air may be determined with information about the concentration of the emissions, the acceptable or the background dilution concentration, and the transformity of wind.
Ecological services for diluting airborne and waterborne pollutants can be calculated as follows (Ulgiati and Brown, 2002):

$$M_{air/water} = d \times (W/c) \qquad \text{Eqn. 2}$$

where, $M_{air/water}$ is the mass of dilution air/water needed, d is the air/ water density, W is the annual amount of the i-th pollutant, and c is the acceptable concentration from agreed regulations or scientific evidence. Eq. (2) should be applied to each released pollutant flow. Using the "acceptable concentration" assumes that some pollution is acceptable. Instead, if the background concentration was used for "c", this would have implied pollution down to a level that is more or less the level before the industrial era. Many more environmental services would be needed than what were actually available, thus placing a constraint to the acceptability of emissions: no emissions that cannot be absorbed or abated by the environment. Once the dilution mass of air or water is known, the energy value of needed environmental services can be referred to in Eq. (1) is determined, by calculating the energy of the dilution air or water. These flows can be of kinetic nature, only if their pollutant transport service is considered, or even of chemical nature, if their ability to drive chemical reactions and abate the pollutants is accounted for. Typical equations are listed as follows.

Release of chemicals into the atmosphere:

$$\left[F_{w.air} = R_{w,air} = N_{kinetic} \times tr_{air} = \frac{1}{2} \times M_{air} \times v^2 \times tr_{wind}\right]_i \qquad (3)$$

Release or conversion of chemicals into water bodies:

$$\left[F_{w,water} = R_{w.water} = N_{chem.} \times tr_{chem,water} = (M_{water} \times G) \times tr_{chem,water}\right]_i \qquad (4)$$

Eqs. (3) and (4) are applied to the i-th released pollutant. $M_{air}$ is the mass and $N_{kinetic}$ is the kinetic energy of dilution air moved by the wind, $tr_{air}$ is assumed to be the

transformity of wind, v is average wind speed, $N_{chem}$ is the chemical available energy of water (equals its ability to drive a chemical transformation), $tr_{chem,water}$ is the transformity of water chemical potential (Odum et al., 2000), G is the Gibbs free energy per unit mass of water relative to reference sea water (4.94 J/g).
If the pollutant is waste heat (assumed released to the atmosphere), we must consider the service of cooling in addition to the service of dilution of chemicals. The cooling calculation procedure starts from the total amount of heat (Q released) released by the system (roughly, the total energy used by the system itself and converted to degraded heat). The heat released to the air increases its temperature from average environmental temperature $T_o$ to a higher newequilibrium temperature $T_e$ considered acceptable by the present legislation or the scientific community. Assuming that the acceptable $T_e$ is only 1°C higher than the average environmental temperature, the following equation should be used:

$$M_{air/water} = \frac{Q_{released}}{\rho} \times (T_e - T_o) = \frac{Q_{released}}{\rho} \times (1^\circ C) \quad (5)$$

where M is the heat-dilution mass required to lower the emission temperatures to the accepted temperature and ρ is an average thermal capacity of air gases. Once the heat-dilution mass for cooling service is known, it can be used in the above Eq. (3) to calculate the additional cooling emergy required. Finally, the total environmental support needed to treat the chemical and heat emissions can be calculated as:

$$R_w = Max\left(R_{w,air,i}\right) + Max\left(R_{w,water,i}\right) \quad (6)$$

It is worth mentioning that this method is proposed without considering – for the sake of simplicity – the diffusion and the chemistry processes in the atmosphere and that it relies on the implicit assumption that the available dilution air/water is always sufficient (which may not be true and would place a limit to the emissions, or require technological treatment, as discussed below in further details).

*Quantifying ecological and economic losses*

A number of methods have been developed in the previous studies for assessing the environmental impact of emissions. It would be a very useful further step to integrate such methods within a procedure capable of describing and quantifying the actual damage to populations or assets in emergy terms, i.e. in terms of lost biosphere work. Examples of such a natural capital and human capital losses are, for example, the decreased biodiversity due to pollution or ecosystem simplification or the economic losses related to damages to human health, land occupation and degradation, damage to human-made assets, among others. In this study, a preliminary damage assessment of losses is performed according to the framework of the Eco-Indicator 99 assessment method (Goedkoop and Spriensma, 2000). Such a method, similar to all endpoint life cycle impact assessment methods, suffers from very large uncertainties intrinsically embodied in its procedure for assessment of final impacts. Yet, it provides a preliminary – although uncertain – estimate of impacts to be used in the calculation procedure of total emergy investment.

In this study, a preliminary damage assessment of losses is performed according to the framework of the Eco-Indicator 99 assessment method (Goedkoop and Spriensma, 2000). Such a method, similar to all endpoint life cycle impact assessment methods, suffers from very large uncertainties intrinsically embodied in its procedure for assessment of final impacts. Yet, it provides a preliminary – although uncertain – estimate of impacts to be used in the calculation procedure of total emergy investment. Damages to natural capital are expressed as the Potentially Disappeared Fraction (PDF) of species in the affected ecosystem, while damages to human health are expressed as Disability Adjusted Life Years (DALY), according toMurray et al. (1994), Goedkoop and Spriensma (2000) and Ukidwe and Bakshi (2007). Using concepts from E.I. 99 (PDF and DALY) to quantify the process impact on ecosystems and human health has the advantage that the assessment relies on damages that can, in principle, be measured or statistically calculated. Unfortunately, the available data in these ecological models are confined to Europe (in most cases to The Netherlands) and their application to assess other countries requires adjustments (Zhang et al., 2010) and calls for urgent database improvement. Moreover, the dose–response relationship considered in the Eco-indicator-99 is linear instead of logistic (Ukidwe and Bakshi, 2007). The latter characteristics suggest themethod can only be applied to slow changes of pollutants concentration and are not suitable for large emissions fluctuations such as environmental accidents. The impact of emissions on human health can be viewed as an additional indirect demand for resource investment. Human resources (considering all their complexity: life quality, education, know-how, culture, social values and structures, hierarchical roles, etc.) can be considered as a local slowly renewable storage that is irreversibly lost due to the polluting production and consumption processes. Societies support the wealth and relations of their components in order to provide shared benefits. When such wealth and relations are lost, the investment is lost and such a lossmust be charged to the process calling for changes and innovation. The emergy loss can be calculated as

$$L^{*}_{w,1} = \sum m^{*}_{i} \times DALY_{i} \times \tau_{H} \qquad (7)$$

Here, $L^{*}_{w,1}$ is the emergy loss in support of the human resource affected, i refers to the ith pollutant, m* is the mass of chemicals released, DALY is its E.I. 99 impact factor and $\tau_H$ is the unit emergy allocated to the human resource per year, calculated as $\tau_H$= total annual emergy/population. The rationale here is that it takes resources to develop a given expertise or work ability and societal organization; when it is lost, new resources must be invested for replacement (not to talk of the value of the individual in itself that is not quantifiable in physical terms).

PDF is the acronym for Potentially Disappeared Fraction of Species (Eco-Indicator 99, Goedkoop and Spriensma, 2000). Such effects can be quantified as the emergy of the loss of local ecological resources, under the same rationale discussed above for the human resource:

$$L^{*}_{w,2} = \sum m^{*}_{i} \times PDF(\%)_{i} \times E_{Bio} \quad (8)$$

where $L^{*}_{w,2}$ is the emergy equivalent of impact of a given emission on urban natural resource, PDF(%) is the fraction potentially affected, measured as PDF x $m^2$ x year x $kg^{-1}$. A damage equal to 1 in E.I. 99 means all species disappear from 1 $m^2$ during 1 year, or 10% of all species disappear from 10 $m^2$ during 1 year, etc. $E_{Bio}$ is the unit emergy stored in the biological resource (seJ x $m^{-1}$ x $year^{-1}$), which is presented as the emergy of local wilderness, farming, forestry, animal husbandry or fishery production. As previously noted, additional emergy loss $L_{w,j}$ should also be included to account for pollution-induced damage to the city assets (e.g., facades of buildings, corrosion of monuments, etc.) according to Ulgiati et al. (1995). This is not, however, included in the present study due to lack of sufficient data.

*Quantifying emergy investment for treatment*

According to Ulgiati et al. (2007) and Cherubini et al. (2009), an additional emergy investment for safe abatement or disposal of waste materials is accounted to compare advantages from decreased damage-related emergy losses. In this study, all the relevant input flows are contained within total purchased emergy. Accordingly, in the case of waste treatments, all the emergy required ($E_w$) is not added to urban total emergy consumption to avoid double counting. Also, the emergy derived from recycled and reused material (flow $F_b$) is not accounted into the exports.

The emergy of the city's wastes (W) in our analysis included industrial waste, MSW (municipal solid waste), sewage, and gaseous emissions that result from the combustion of fossil fuels and from incineration of MSW. To evaluate urban waste emergy, the emergy inputs in the form of labor, fuel, water, electricity, and capital (machines) must be accounted for, in addition to the emergy of all wastes that represent inputs and outputs in the treatment processes (Fig. 4). Due to the uncertainty of available data, only reused material in solid waste treatment processes (methane and compostable matter) are calculated. Finally, damage associated with solid waste generation can be measured by land occupation for landfill and disposal. This may be converted to emergy via the emergy/area ratio (upper bound, average emergy density of economic activities) or even via the emergy intensity of soil formation (lower bound, average environmental intensity). Thus the related emergy loss ($L_{w,3}$) can be obtained using the total occupied land area multiplied by the economic or environmental emergy intensity of such an area (choice depends on the area of the investigated system).

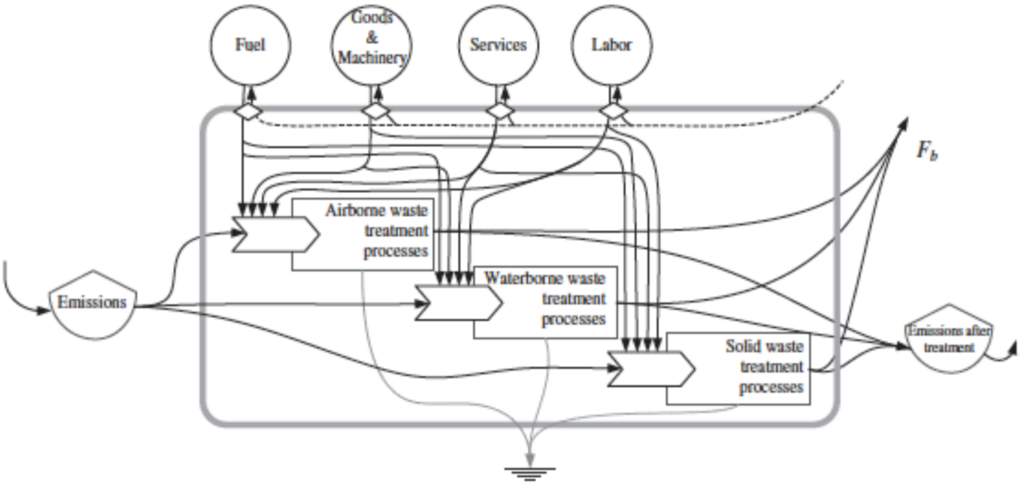



Fig. 4. Aggregated diagram of emergy contribution from different sources to airborne, waterborne and solid waste treatment system.

*The corresponding emergy-based performance metrics*

Based on emergy accounting and quantification of the emissions' impacts, several performance metrics can be evaluated (Odum, 1996; Brown and Ulgiati, 1997). These performance metrics can be listed as follows.

(1) Emergy yield ratio

$$EYR = U / (F + G + P_2I + P_2I_3) \qquad (9)$$

Here, U is the total emergy used (U=R+N+F+G+P2I+P2I3), R is the locally renewable environmental resources, N is nonrenewable resources, F is imported fuels, G is imported goods and minerals, P2I is purchased services, and P2I3 is emergy paid for imported labor. As the ratio of total emergy input to imported emergy, EYR indicates the efficacy of the system to make use of economic investment. By comparing EYR values, one can understand the reliance of a process on local resources or its dependence on imports. The higher the value of EYR is, the higher its ability to exploit local renewable or nonrenewable resources. Of course, if renewable resources are exploited, the process is sustainable; if nonrenewables are exploited, an excess exploitation rate may make the process nonsustainable. When additional emergy input flows associated with natural capital or human capital losses are accounted, the ratio becomes as is in Eq. (10), where emergy losses are considered as indirect input flows to be provided again for the replacement of the lost capital and the system to be sustainable.

$$EYR' = \left(U + E_w^* + L_{w,1}^* + L_{w,2}^* + L_{w,3} - F_b\right) \div \left(F + G + P_2I + P_2I_3 + U_w^* + L_{w,1}^* + L_{w,2}^* + L_{w,3} - F_b\right) \quad (10)$$

(2) Environmental loading ratio

The Environmental Loading Ratio (ELR) is defined in Eq. (11). It is the ratio of the sum of local nonrenewable emergy and purchased emergy (including services) to the locally renewable emergy. Here, renewable fraction of imported labor and services for imports is 10%, which equals the agricultural self-sufficiency rate. Being ELR the ratio of nonrenewable and imported resources to locally renewable, it indicates the intensity of the indirect environmental resource contribution to a socio-economic system. A system with a higher ratio depends more heavily on indirect resources, compared to a fully natural system that only depends on locally renewable R. The higher the ratio is, the greater the stress on the local environmental resource.

$$ELR = N + G + F + P2I + P2I3/R \quad (11)$$

Eq. (12) expresses a modified ELR accounting for the additional emergy input flows associated to natural capital or human capital losses.

$$ELR' = \left(N + G + F + P_2I + P_2I_3 + U_w^* + L_{w,1}^* + L_{w,2}^* + L_{w,3} - F_b\right) / R \quad (12)$$

(3) Emergy-based sustainability index, calculated after Eqs. (9)–(12) above.

$$ESI = EYR / ELR \quad (13)$$
$$ESI' = EYR' / ELR' \quad (14)$$

This index is an aggregate measure of the economic benefit (EYR) per unit of environmental loading (ELR). Eq. (14) applies when losses of natural and human made capital are also included.

*The determination of pollutants*

Our study will deal with the harmful emissions for the human health and ecosystem listed in Table 1. Air emissions discharge from both urban production and use including $SO_2$, dust, NOx and $CH_4$ (respiratory disorders), $CO_2$, $N_2O$ and $CH_4$ (climate change). The data related to $SO_2$, dust, and $NO_x$ were collected from governmental publications, such as the Beijing Statistical Yearbook and the Chinese Environmental Statistical Yearbook (BSY, 2000–2007; CESY, 2000–2007). Data about $CO_2$, $N_2O$ and $CH_4$ are calculated as greenhouse gases released at local and global scales, based on direct and indirect energy consumption, which in turn are evaluated according to the Embodied Energy Analysis method (Slesser, 1974; Herendeen, 2004). The embodied energy of materials and energy flows is calculated by multiplying local inputs by appropriate Oil Equivalent Factors.

**Table 1**
List of emissions and environmental impacts.

| | | Source[a] | Damage category human health | DALY/kg of emission | Damage category ecosystem quality | PDF×$m^2$× year |
|---|---|---|---|---|---|---|
| Airborne pollution | $CO_2$ | p/c | Climate change | 2.10E−07 | | |
| | $NO_x$ | p/c | Respiratory disorders | 8.87E−05 | Acidification | 5.71E+00 |
| | $SO_2$ | p/c | Respiratory disorders | 5.46E−05 | Acidification | 1.04E+00 |
| | Dust | p/c | Respiratory disorders | 3.75E−04 | | |
| | $N_2O$ | p/c | Climate change | 6.90E−05 | | |
| | $CH_4$ | p/c | Respiratory disorders | 1.28E−08 | | |
| | $CH_4$ | p/c | Climate change | 4.40E−06 | | |
| Waterborne pollution | Mercury | p | | | Ecotoxic emissions | 1.97E+02 |
| | Cadmium | p | Carcinogenic effects | 7.12E−02 | Ecotoxic emissions | 4.80E+02 |
| | Hexavalent Chromium | p | Carcinogenic effects | 3.43E−01 | | |
| | Lead | p | | | Ecotoxic emissions | 7.39E+00 |
| | Arsenic | p | Carcinogenic effects | 6.57E−02 | Ecotoxic emissions | 1.14E+01 |
| | Volatile phenol | p | Carcinogenic effects | 1.05E−05 | | |
| | Cyanide | p | Carcinogenic effects | 4.16E−05 | | |
| | Oil | p | Carcinogenic effects | 4.16E−05 | | |
| | COD | p/c | Eutrophication[b] | n.a. | Eutrophication[b] | n.a. |
| | $NH_4$–H | p/c | Eutrophication[b] | n.a. | Eutrophication[b] | n.a. |

Note: a. p means pollutions come from urban production, c means pollutions come from urban use process;
b. The ecological losses caused by COD and NH4-N were not considered due to lack in the corresponding data.

*Results and discussion*

For the purpose of exploring the trend of Beijing sustainability dynamics during its recent economic growth, Tables 2(a), 2(b) and 2(c) respectively list the evaluated emergy values of the detailed flows, reflecting the general economic situation of the Beijing. The input to the process is aggregated into five categories, i.e., free renewable environmental resources (R), exploited local nonrenewable resources (N), imported fuels and minerals (F), imported goods (G) and purchased services (P2I). Correspondingly, the operation for all the processes above will inevitably produce environmental impacts. The direct and indirect inflows in different urban developing processes will be calculated in the following section.

**Table 2(a)**
Emergy flows supporting urban metabolic system in 2006.

| Items | Units | Raw amount | Transformity* (sej/unit) | Ref. trans. | Emergy (sej/year) |
|---|---|---|---|---|---|
| *Free renewable environmental resources* | | | | | |
| 1 Sun | J/year | 7.02E+19 | 1 | by definition | 7.02E+19 |
| 2 Kinetic energy of wind | J/year | 4.87E+16 | 2.51E+03 | Odum et al., 2000 | 1.22E+20 |
| 3 Rainfall (geopotential energy) | J/year | 1.25E+15 | 1.74E+04 | Odum et al., 2000 | 2.19E+19 |
| 4 Rainfall (chemical potential) | J/year | 1.12E+16 | 3.05E+04 | Odum et al., 2000 | 3.43E+20 |
| 5 Geothermal heat | J/year | 1.79E+16 | 5.76E+04 | Odum et al., 2000 | 1.03E+21 |
| *Exploited local nonrenewable resources* | | | | | |
| 6 Top soil loss | J/year | 3.17E+14 | 1.23E+05 | Odum et al., 2000 | 3.90E+19 |
| 7 Coal | J/year | 2.04E+17 | 6.69E+04 | Odum et al., 2000 | 1.37E+22 |
| 8 Minerals | | | | | |
| Limestone | g/year | 1.52E+13 | 1.68E+09 | Brandt-Williams, 2001 | 2.55E+22 |
| Sand and gravel | g/year | 1.02E+13 | 1.68E+09 | Brandt-Williams, 2001 | 1.70E+22 |
| Iron ore | g/year | 1.68E+13 | 1.44E+09 | Odum et al., 2000 | 2.41E+22 |

Calculations:

1. Sun: average insolation = 5.36E+09 J/m$^2$/year, total area of Beijing region = 1.64E+04 km$^2$, continental albedo = 0.201. Solar energy received = (total area of Beijing region)(average insolation)(1 − albedo) = (1.64E+04 km$^2$ × 10$^6$)(5.36E+09 J/m$^2$/year)(1 − 0.201) = 7.02E+19 J/year.
2. Kinetic energy of wind: air density = 1.3 kg/m$^3$, wind velocity (annual average) = 2.5 m/s, observed winds are about 0.6 of geostrophic wind, drag coefficient = 1.00E−03, Time frame = 365 × 24 × 60 × 60 = 3.15E+07 s/year. Wind energy = (air density)(drag coeff.)(geostrophic wind velocity)$^3$(total area)(time frame) = (1.3 kg/m$^3$)(1.00E−03)(2.5 m/s/0.6)$^3$(1.64E+04 km$^2$ × 10$^6$)(3.15E+07 s/year) = 4.87E+16 J/year.
3. Rainfall (geopotential energy): total agricultural area of Beijing = 1.64E+10 m$^2$, rain (annual average) = 0.318 m/year, average elevation = 43.5 m, runoff rate = 56.40%. Energy = (total area)(rainfall)(% runoff)(avg elevation)(gravity) = (1.64E+04 km$^2$ × 10$^6$)(0.318 m/year)(56.40%)(43.5 m)(9.8 kg/m$^2$) = 1.25E+15 J/year.
4. Rainfall (chemical potential energy): water density = 1.00E+06 g/m$^3$, mass of rainfall water = (rainfall)(total area)(water density) = (0.318 m/year)(1.64E+04 km$^2$ × 10$^6$)(1.00E+06 g/m$^3$) = 5.22E+15 g/year, fraction of water that is evapotranspired = 44%, Gibbs free energy of water = 4.94 J/g. Energy = (evapotranspired water)(Gibbs free energy per gram water) = (5.22E+15 g/year)(44%)(4.94 J/g) = 1.12E+16 J/year.
5. Geothermal heat: average heat flow per area = 3.50E−02 J/m$^2$/s. Energy = (land area)(heat flow per area) = 1.79E+16 J/year.
6. Net loss of organic matter in topsoil: soil erosion rate = 8.15E+02 g/m$^2$/year, average% organic in soil = 0.02, assuming water content in organic matter = 0.7, energy content of dry organic matter = 5.00 kcal/g. Energy = (total agricultural area)(erosion rate)(% organic)(1 − water content in organic matter)(energy content of dry organic matter)(4186 J/kcal) = (1.64E+10 m$^2$)(8.15E+02 g/m$^2$/year)(0.02)(1 − 0.7)(5.00 kcal/g)(4186 J/kcal) = 3.17E+14 J/year.
7. Fuels input from local region: coal = 6.42E+06 t/year, coal energy = (6.42E+06 t/year)(3.18E+10 J/t) = 2.04E+17 J/year; Oil = 0.00E+00 t/year (BSY, 2000–2007), oil energy = (0.00E+00 t/year)(4.30E+10 J/t) = 0.00E+00 J/year; Natural gas = 0.00E+00 m$^3$ (BSY, 2000–2007), natural gas energy = (0.00E+00 m$^3$)(0.7174 kg/m$^3$) = 0.00E+00 J/year.
8. Constructed local input: cement quantity of production = 1.27E+07 t/year, assuming 1.2 t limestone and 1.6 t sand and gravel are needed to produce 1 t cement and 50% of sand and gravel is from local regain, limestone = 1.52E+13 g/year, sand and gravel = 1.02E+13 g/year, iron ore = 1.68E+07 t = 1.68E+13 g/year.

* References for transformities (conversion from global emergy baseline of 9.44E+24 to 15.83E+24 sej/year).

*Direct and indirect inflow analysis for urban production and consuming processes*

*Direct emergy input associated with emissions and ecological services*

Ulgiati and Brown (2002) focused on free environmental services and the advantage of relying on the existing cycles and processes of the biosphere in order to avoid the need for additional investment for damage fixing (what they referred to as an "entropy trap"). Such a strategy requires that by-products are only released in amounts that can be absorbed and recycled by naturewith little or no additional resource investment, which means that emissions exceeding the ecological services capacity are not sustainable. The ecological services needed to dilute airborne and waterborne pollutants are shown in Table 3 where the largest value among all is chosen as representative of the order of magnitude of the needed environmental work. The reference "acceptable" concentrations for calculation (Eqs. (2) and (3)) refer to both Ground Water Quality Standard of China (GB3838-2002) and Air Quality Standard of China (GB3095-1996) (here, the average value for wind speed was assumed to be 2.50 m/s in a year).

**Table 2(b)**
Emergy imports for urban metabolic system in 2006.

| Items | Units | Raw amount | Transformity (seJ/unit) | Ref. trans. | Emergy (seJ/year) |
|---|---|---|---|---|---|
| 9 Hydroelectricity | J/year | 2.30E+14 | 3.36E+05 | Odum et al., 2000 | 7.74E+19 |
| 10 Stream flow | J/year | 8.81E+15 | 3.05E+04 | Brandt-Williams, 2001 | 2.69E+20 |
| 11 Fuels import | | | | | |
| Coal | J/year | 7.04E+17 | 6.69E+04 | Odum et al., 2000 | 4.83E+22 |
| Coke | J/year | 4.72E+16 | 1.10E+05 | Bastianoni et al., 2009 | 5.18E+21 |
| Crude oil | J/year | 3.45E+17 | 9.08E+04 | Bastianoni et al., 2009 | 3.13E+22 |
| Gasoline | J/year | 9.20E+16 | 1.05E+05 | Bastianoni et al., 2009 | 9.64E+21 |
| Kerosene | J/year | 1.23E+17 | 1.10E+05 | Bastianoni et al., 2009 | 1.36E+22 |
| Diesel Oil | J/year | 8.61E+16 | 1.10E+05 | Bastianoni et al., 2009 | 9.48E+21 |
| Fuel Oil | J/year | 4.42E+15 | 1.10E+05 | Bastianoni et al., 2009 | 4.87E+20 |
| Liquefied petroleum gas (LPG) | J/year | 6.66E+15 | 1.11E+05 | Bastianoni et al., 2009 | 7.37E+20 |
| Natural gas | J/year | 1.58E+17 | 9.85E+04 | Romitelli, 2000 | 1.56E+22 |
| 12 Electricity | J/year | 1.47E+17 | 1.74E+05 | Odum et al., 2000 | 2.57E+22 |
| 13 Imported goods | | | | | |
| 13.1 Imported food, livestock and products | | | | | |
| Grain | J/year | 1.91E+16 | 1.14E+05 | Yan and Odum, 1998 | 2.18E+21 |
| Rapeseed | J/year | 8.23E+16 | 8.88E+04 | Odum et al., 1987 | 7.31E+21 |
| Vegetable | J/year | 1.42E+14 | 7.37E+04 | Odum et al., 1987 | 1.05E+19 |
| Fruit | J/year | 2.30E+13 | 8.88E+04 | Ulgiati et al., 1994 | 2.04E+18 |
| Meat | J/year | 2.75E+09 | 5.31E+06 | Yan and Odum, 1998 | 1.46E+16 |
| Milk | J/year | 2.36E+11 | 3.35E+06 | Yan and Odum, 1998 | 7.90E+17 |
| 13.2 Imported raw and processed materials | | | | | |
| Wood | J/year | 1.51E+15 | 5.36E+04 | Odum et al., 2000 | 8.11E+19 |
| Iron ores | g/year | 4.68E+13 | 1.44E+09 | Odum et al., 2000 | 6.72E+22 |
| Sand and gravel | g/year | 1.02E+13 | 1.68E+09 | Brandt-Williams, 2001 | 1.70E+22 |
| Paper and paperboard | J/year | 1.20E+15 | 7.37E+04 | Lan and Odum, 2004 | 8.85E+19 |
| Silk | J/year | 6.39E+11 | 1.12E+07 | Odum et al., 2000 | 7.18E+18 |
| Wool, animal hair | J/year | 1.32E+14 | 7.37E+06 | Odum et al., 2000 | 9.70E+20 |
| 13.3 Imported goods | | | | | |
| Polythene (PE) | g/year | 7.30E+10 | 4.69E+09 | Brown and Ulgiati, 2004 | 3.43E+20 |
| Polypropylene(PP) | g/year | 1.60E+10 | 4.69E+09 | Brown and Ulgiati, 2004 | 7.51E+19 |
| Polystyrene (PS) | g/year | 1.10E+10 | 4.69E+09 | Brown and Ulgiati, 2004 | 5.16E+19 |
| Other coke chemicals | g/year | 2.54E+10 | 4.89E+09 | Brown and Ulgiati, 2004 | 1.24E+20 |
| Other petroleum products | g/year | 1.16E+12 | 4.89E+09 | Brown and Ulgiati, 2004 | 5.69E+21 |
| Iron and steel | g/year | 2.70E+13 | 3.16E+09 | Bargigli and Ulgiati, 2003 | 8.53E+22 |
| Aluminum and articles | g/year | 1.20E+12 | 7.74E+08 | Odum et al., 2000 | 9.29E+20 |
| 13.4 Other metals and articles | g/year | 2.16E+11 | 4.74E+09 | Odum et al., 2000 | 1.02E+21 |
| 13.5 Hi-tech products, machinery and electrical equipment | | | | | |
| Steel | g/year | 3.65E+09 | 3.16E+09 | Bargigli and Ulgiati, 2003 | 1.15E+19 |
| Aluminum | g/year | 1.65E+09 | 7.74E+08 | Odum et al., 2000 | 1.28E+18 |
| Copper | g/year | 1.20E+09 | 3.36E+09 | Brown and Ulgiati, 2004 | 4.05E+18 |
| Other metals | g/year | 4.20E+09 | 4.74E+09 | Odum et al., 2000 | 1.89E+19 |
| Ceramics/Glasses | g/year | 1.69E+10 | 3.18E+09 | Brown and Ulgiati, 2004 | 5.37E+19 |
| Plastics | g/year | 6.09E+09 | 7.21E+09 | Odum et al., 2000 | 4.39E+19 |
| 13.6 Transport equipment | | | | | |
| Steel | g/year | 1.88E+10 | 3.16E+09 | Bargigli and Ulgiati, 2003 | 5.94E+19 |
| Aluminum | g/year | 3.21E+09 | 7.74E+08 | Odum et al., 2000 | 2.48E+18 |
| Rubber and plastic material | g/year | 2.29E+08 | 7.21E+09 | Odum et al., 2000 | 1.65E+18 |
| Copper | g/year | 6.87E+08 | 3.36E+09 | Brown and Ulgiati, 2004 | 2.31E+18 |
| 13.7 Electronic goods (estimated from component materials) | | | | | |
| Ferrous metal | g/year | 1.25E+09 | 3.16E+09 | Bargigli and Ulgiati, 2003 | 3.94E+18 |
| Silica/glass | g/year | 1.62E+09 | 3.18E+09 | Odum et al., 2000 | 5.16E+18 |
| Copper | g/year | 4.36E+08 | 3.36E+09 | Brown and Ulgiati, 2004 | 1.47E+18 |
| Plastics | g/year | 1.43E+09 | 7.21E+09 | Odum et al., 2000 | 1.03E+19 |
| Aluminum | g/year | 8.72E+08 | 7.74E+08 | Odum et al., 2000 | 6.75E+17 |
| Other metal | g/year | 4.98E+08 | 4.74E+09 | Odum et al., 2000 | 2.36E+18 |
| 14 Imported human labor (commuters) | $/year | 7.30E+08 | 5.00E+12 | This study, country emergy/$ ratio | 3.65E+21 |
| 15 Services associated to imports | | | | | |
| From other provinces | $/year | 1.80E+10 | 5.00E+12 | This study, country emergy/$ ratio | 9.02E+22 |
| Import | $/year | 1.05E+10 | 1.13E+12 | This study, world emergy/$ ratio | 1.19E+22 |
| Size of specific sectors | | | | | |
| 16 Tourism | $/year | 2.30E+10 | 5.00E+12 | This study, country emergy/$ ratio | 1.15E+23 |

9. Hydroelectricity: Hydroelectricity = 6.40E+07 kwh/year. Energy = (6.40E+07 kwh/year)(3.60E+06 J/kwh) = 2.30E+14 J/year.
10. Stream flow: upstream inflow = 1.78E+09 $m^3$/year, coefficient = 4.94E+06 J/$m^3$. Energy = (upstream inflow)(coefficient) = (1.78E+09 $m^3$/year)(4.94E+06 J/$m^3$) = 8.81E+15 J/year.
11. Fuel import: coal = 2.68E+07 t/year, coal energy = (2.68E+07 t/year)(3.18E+10 J/t) = 7.04E+17 J/year; coke = 1.66E+06 t/year, coke energy = (1.66E+06 t/year)(2.85E+10 J/t) = 4.72E+16 J/year; crude oil = 8.09E+06 t/year, oil energy = (8.09E+06 t/year)(4.30E+10 J/t) = 3.45E+17 J/year; gasoline = 1.97E+06 t/year, gasoline energy = (1.97E+06 t/year)(4.67E+10 J/t) = 9.20E+16 J/year; kerosene = 1.23E+17 t/year, kerosene energy = (1.23E+17 t/year)(4.30E+10 J/t) = 1.23E+17 J/year; diesel oil = 2.00E+06 t/year, diesel oil energy = (2.00E+06 t/year)(4.30E+10 J/t) = 8.61E+16 J/year; fuel oil = 1.04E+05 t/year, fuel oil energy = (1.04E+05 t/year)(4.26E+10 J/t) = 4.42E+15 J/t; LPG = 1.56E+05 t/year, LPG energy = (1.56E+05 t/year)(4.26E+10 J/t) = 6.66E+15 J/t; natural gas = 4.06E+09 $m^3$, natural gas energy = (4.06E+09 $m^3$)(3.89E+07 J/$m^3$) = 1.58E+17 J/year.
12. Electricity: electricity = 4.10E+10 kwh/year. Energy = (4.10E+10 kwh/year)(3.60E+06 J/kwh) = 1.47E+17 J/year.

13.1 Imported food, livestock and products: grain = 1.32E+06 t/year, grain energy = (1.32E+06 t/year × 1000)(1.45E+07 J/kg) = 1.91E+16 J/year; rapeseed = 3.29E+06 t/year, rapeseed energy = (3.29E+06 t/year × 1000)(2.50E+07 J/kg) = 8.23E+16 J/year; vegetable = 1.01E+04 t/year, vegetable energy = (1.01E+04 t/year × 1000)(1.41E+07 J/kg) = 1.42E+14 J/year; fruit = 1.00E+04 t/year, fruit energy = (1.00E+04 t/year × 1000)(2.30E+06 J/kg) = 2.30E+13 J/year; meat = 3.94E+02 t/year, meat energy = (3.94E+02 t/year × 1000)(6.99E+06 J/kg) = 2.75E+09 J/year; milk = 8.04E+04 t/year, milk energy = (8.04E+04 t/year × 1000)(2.93E+06 J/kg) = 2.36E+11 J/year.

13.2 Imported raw and processed materials: wood = 1.89E+05 $m^3$/year, wood energy = (1.89E+05 $m^3$/year)(8.00E+09 J/$m^3$) = 1.51E+15 J/year; iron ores, sand and gravel are from; paper and paperboard = 6.00E+07 t/year, paper and paperboard energy = (6.00E+07 t/year)(2.00E+07 J/t) = 1.20E+15 J/year; silk = 3.40E+07 kg/year, silk energy = (3.40E+07 kg/year/1000)(1.88E+07 J/t) = 6.39E+11 J/year; wool, animal hair = (7.00E+06 t/year)(1.88E+07 J/t) = 1.32E+14 J/year.

**Table 2(c)**
Additional resources input for the waste treatment processes in 2006.

| Items | Units | Raw amount | Transformity (seJ/unit) | Ref. trans. | Emergy (seJ/year) |
|---|---|---|---|---|---|
| *Waterborne waste treatment processes* | | | | | |
| 17 Electricity | J/year | 1.48E+15 | 1.74E+05 | Odum et al., 2000 | 2.58E+20 |
| 18 Chemical products | | | | | |
| Phosphorus removal reagent | kg/year | 4.26E+06 | 4.44E+12 | Grönlund et al., 2004 | 1.89E+19 |
| Flocculating reagent | kg/year | 3.53E+05 | 4.44E+12 | Grönlund et al., 2004 | 1.57E+18 |
| Hydrochloric acid | kg/year | 8.24E+06 | 4.44E+12 | Grönlund et al., 2004 | 3.66E+19 |
| Sodium chlorate | kg/year | 2.05E+06 | 4.44E+12 | Grönlund et al., 2004 | 9.10E+18 |
| 19 Labor | $/year | 1.72E+07 | 7.47E+12 | This study | 1.28E+20 |
| 20 Service embodied in fuels and goods | $/year | 1.30E+08 | 7.47E+12 | This study | 9.74E+20 |
| *Airborne waste treatment processes* | | | | | |
| 21 Electricity | J/year | 1.06E+15 | 1.74E+05 | Odum et al., 2000 | 1.84E+20 |
| 22 Chemical products | | | | | |
| Desulfurizer | kg/year | 9.52E+07 | 4.69E+12 | Brown and Ulgiati, 2004 | 4.47E+20 |
| 23 Labor | $/year | 1.29E+07 | 7.47E+12 | This study | 9.62E+19 |
| 24 Service embodied in fuels and goods | $/year | 5.04E+07 | 7.47E+12 | This study | 3.77E+20 |
| *Solid waste treatment processes* | | | | | |
| 25 Electricity | J/year | 6.64E+12 | 1.74E+05 | Odum et al., 2000 | 1.16E+18 |
| 26 Garbage truck | | | | | |
| Garbage truck (steel) | g/year | 5.58E+10 | 3.16E+09 | Bargigli and Ulgiati, 2003 | 1.76E+20 |
| Garbage truck (plastic and tires) | g/year | 6.20E+09 | 7.21E+09 | Odum et al., 2000 | 4.47E+19 |
| Diesel for truck | J/year | 1.10E+13 | 1.10E+05 | Odum et al., 2000; Bastianoni et al., 2009 | 1.21E+18 |
| 27 Auxiliary fuel for incineration | | | | | |
| Coal | J/year | 1.29E+14 | 6.69E+04 | Odum, 1996 | 8.61E+18 |
| Oil | J/year | 8.35E+12 | 9.08E+04 | Odum et al., 2000; Bastianoni et al., 2009 | 7.58E+17 |
| 28 Chemical products for incineration | | | | | |
| Limestone | g/year | 2.94E+09 | 1.68E+09 | Brandt-Williams, 2001 | 4.93E+18 |
| Carbonate | g/year | 2.94E+08 | 1.68E+09 | Brandt-Williams, 2001 | 4.93E+17 |
| 29 Labor | $/year | 4.87E+07 | 7.47E+12 | This study | 3.64E+20 |
| 30 Service embodied in Fuels and Goods | $/year | 1.45E+07 | 7.47E+12 | This study | 1.08E+20 |
| *Recycle and reuse part of the emissions* | | | | | |
| 31 Methane | kg/year | 1.30E+07 | 5.22E+04 | Odum, 1996 | 6.78E+11 |
| 32 Fertilizer | kg/year | 4.90E+10 | 2.68E+09 | Odum et al., 2000 | 1.31E+20 |

17. Electricity: electricity consumption rate for waterborne waste treatment processes = 2.50E−01 kwh/t, treated water = 1.65E+09 t/year. Energy = (2.50E−01 kwh/year)(1.65E+09 t/year)((3.60E+06 J/kwh) = 1.48E+15 J/year.
18. Chemical products: rough estimate of the chemical products input is given based on simplistic assumption that all the plants adopt the craft of orbal oxidation ditch. Thus, phosphorus removal reagent = (2.59E−09 kg/t)(1.65E+09 t/year) = 4.26E+06 kg/year (Zhang et al., 2010), flocculating reagent = (2.15E−10 kg/t)(1.65E+09 t/year) = 3.53E+05 kg/year (Zhang et al., 2010), hydrochloric acid = (5.01E−09)(1.65E+09 t/year) = 8.24E+06 kg/year (Zhang et al., 2010), sodium chlorate = (1.25E−09)(1.65E+09 t/year) = 2.05E+06 kg/year (Zhang et al., 2010).
19. Labor: labor in waterborne waste treatment = 4.50E+03 se, average wage = 2.98E+04 yuan/se/year. Labor = (4.50E+03 se)(2.98E+04 yuan/se/year)/(7.81 yuan/$) = 1.72E+07 $/year.
21. Electricity: coal-fired generators = 2.10E+10 kwh/year, electricity consumption per electricity generation for airborne waste treatment processes = 1.4%. Energy = (2.10E+10 kwh/year)(1.4%)(3.60E+06 J/kwh) = 6.64E+12 J/year.
22. Chemical products: desulfurizer consumption rate = 1.40 t/t $SO_2$, $SO_2$ remove = 6.80E+04 t/year. Desulfurizer = (1.40 t/t $SO_2$)(6.80E+04 t/year) × 1000 = 9.52E+07 kg/year.
23. Labor: labor in airborne waste treatment = 3.38E+03 se, Labor = (3.38E+03 se)(2.98E+04 yuan/se/year)/(7.81 yuan/$) = 1.29E+07 $/year.
25. Electricity: electricity for compost = 9.42 kwh/t. Energy = (9.42 kwh/t)(1.96E+05 t/year)((3.60E+06 J/kwh) = 6.64E+12 J/year.
26. Garbage truck: garbage truck number = 6197, Average mass of trucks = 1.00E+4 kg, fraction of trucks is steel = 90%, Fraction of trucks is plastic material and tires = 10%, average lifetime = 10 year, average diesel for truck = 57,000 × 0.725 kg/year. Energy diesel = (57,000 × 0.725 kg/year) × 6197 × (43,000 J/kg) = 1.10E+13 J/year.
27. Auxiliary fuel for incineration: incineration = 9.80E+04 t/year, auxiliary coal per incineration = 5.00E−02 t/t, auxiliary oil per incineration = 2.00E−03 t/t.
28. Chemical products for incineration: limestone per incineration = 3.00E−02 t/t, carbonate per incineration = 3.00E−03 t/t.
29. Labor: labor in solid waste treatment = 3.80E+04 se, average wage of sorting worker = 1.00E+04 yuan/se/year, labor = (3.80E+04 se)(1.00E+04 yuan/se/year)/(7.81 yuan/$) = 4.87E+07 $/year.
31. Methane: landfills (garbage) = 4.68E+06 t/year (BESY, 2007), methane yield per landfills = 90 $m^3$/t, density = 0.77 kg/$m^3$, collection rate = 4%. Methane = (4.68E+06 t/year)(90 $m^3$/t)(0.77 kg/$m^3$)(4%) = 1.30E+07 kg/year.
32. Fertilizer: fertilizer yield rate = 25%. Fertilizer = (4.68E+06 t/year) × 25% × 1000 = 4.90E+10 kg/year.

Results show that urban consumption processes released more waterborne emissions than urban production activities over the investigated period, while for airborne emissions the two types of activities are quite close and the emergy values of ecological service are far less than that for waterborne pollutants. Therefore, Beijing should emphasize more on waterborne emission control in consumption activities (households, transportation services and other services). The largest emergies of environmental services which needed to dilute the airborne pollutant were calculated based on the need for dilution of sulfur dioxide in both two types of activities, and the various trajectories of these emergy inputs decreased over time, from 7.30 x $10^{19}$ to 3.95 x $10^{19}$ seJ/year in consumption process and from 1.25 x $10^{19}$ 4.53 x $10^{20}$ seJ/year in production activities. Meanwhile, out of all the waterborne pollutants, ecological services were mainly used to dilute $NH_3$–N. Although the environmental services associated to consumption phase declined sharply after 2003, the emergy values of needed abatement services was still more than 10 times larger than that in production process during 2003–2006. It is worth mentioning that, in this study, only a rough accounting is performed to ascertain the environment ability to absorb, dilute and process the undesired by-products. However, the hypothesis is made that the ecological services available over the whole urban area can support the actual pollution and achieve a dilution to the legal acceptable concentration. Beijing's total amount of surface water was 7.6 x $10^8$ $m^3$ in 2006, while the demand for dilution is still around 3.0 x $10^8$ $m^3$. Requiring dilution to the background concentration would demand many more water-related dilution services, but such a higher demand is not taken into account in this study. However, even if the environmental background value is not considered, dilution might still be insufficient due to the obstacles to the water cycle in Beijing placed by the existing small reservoirs and public water facilities. In other words, the demand for clean water to dilute might exceed the locally available resource.

**Table 3**
Ecological services needed to dilute some airborne and waterborne pollutants (seJ/year).

| | | Ref. concentration | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 |
|---|---|---|---|---|---|---|---|---|---|---|
| $R^*_{w-c}$ | | | | | | | | | | |
| 1 | $SO_2$ | 2.00E−02 $mg/m^3$ | 7.30E+19 | 7.57E+19 | 6.22E+19 | 5.65E+19 | 5.96E+19 | 3.18E+19 | 3.78E+19 | 3.95E+19 |
| 2 | Dust | 8.00E−02 $mg/m^3$ | 1.30E+18 | 1.33E+18 | 1.33E+18 | 1.53E+18 | 1.80E+18 | 4.96E+18 | 4.45E+18 | 4.21E+18 |
| 3 | $NO_x$ | 5.00E−02 $mg/m^3$ | 1.64E+19 | 1.51E+19 | 1.35E+19 | 1.61E+19 | 1.82E+19 | 1.35E+19 | 2.24E+19 | 2.70E+19 |
| 4 | Heat released | Assumption | 3.05E+18 | 2.96E+18 | 2.57E+18 | 2.58E+18 | 3.57E+18 | 3.99E+18 | 4.13E+18 | 4.91E+18 |
| 5 | COD | 1.50E+01 mg/L | 7.21E+20 | 7.79E+20 | 7.47E+20 | 7.18E+20 | 6.91E+20 | 1.19E+21 | 1.05E+21 | 1.01E+21 |
| 6 | $NH_4$-N | 1.50E−01 mg/L | 2.25E+22 | 4.87E+22 | 4.67E+22 | 4.80E+22 | 4.18E+22 | 1.62E+22 | 1.31E+22 | 1.21E+22 |
| $R^*_{w-c-air}$ | Max(1:4) | | 7.30E+19 | 7.57E+19 | 6.22E+19 | 5.65E+19 | 5.96E+19 | 3.18E+19 | 3.78E+19 | 3.95E+19 |
| $R^*_{w-c-water}$ | Max(5:6) | | 2.25E+22 | 4.87E+22 | 4.67E+22 | 4.80E+22 | 4.18E+22 | 1.62E+22 | 1.31E+22 | 1.21E+22 |
| $R^*_{w-p}$ | | | | | | | | | | |
| 7 | $SO_2$ | 2.00E−02 $mg/m^3$ | 1.25E+20 | 1.01E+20 | 7.35E+19 | 6.12E+19 | 5.50E+19 | 6.05E+19 | 4.67E+19 | 4.53E+19 |
| 8 | Dust | 8.00E−02 $mg/m^3$ | 1.24E+19 | 1.01E+19 | 7.76E+18 | 7.04E+18 | 7.40E+18 | 7.77E+18 | 5.67E+18 | 5.43E+18 |
| 9 | $NO_x$ | 5.00E−02 $mg/m^3$ | 6.99E+18 | 7.21E+18 | 7.76E+18 | 8.89E+18 | 1.10E+19 | 8.54E+18 | 1.40E+19 | 1.81E+19 |
| 10 | Heat released | Assumption | 7.49E+18 | 6.93E+18 | 5.83E+18 | 6.01E+18 | 7.38E+18 | 8.47E+18 | 8.48E+18 | 8.90E+18 |
| 11 | Cadmium | 1.00E−04 mg/L | n.a. | n.a. | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 3.01E+17 |
| 12 | Chromium | 1.00E−02 mg/L | 6.03E+18 | 4.52E+18 | 3.01E+18 | 1.51E+18 | 6.78E+17 | 1.79E+18 | 5.12E+17 | 1.37E+18 |
| 13 | Lead | 1.00E−02 mg/L | 7.53E+18 | 6.03E+18 | 4.52E+18 | 3.01E+18 | 2.34E+18 | 1.07E+18 | 1.04E+18 | 3.16E+17 |
| 14 | Arsenic | 1.00E−02 mg/L | 3.01E+17 | 1.51E+17 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 15 | Volatile phenol | 2.00E−03 mg/L | 8.21E+20 | 6.03E+20 | 2.26E+20 | 1.13E+20 | 5.49E+19 | 3.22E+19 | 4.11E+19 | 5.85E+19 |
| 16 | Cyanide | 1.00E+00 mg/L | 8.29E+17 | 6.03E+17 | 3.77E+17 | 1.51E+17 | 6.03E+16 | 4.52E+16 | 7.53E+16 | 1.51E+16 |
| 17 | COD | 1.50E+01 mg/L | 3.05E+20 | 2.51E+20 | 2.01E+20 | 1.51E+20 | 1.05E+20 | 1.14E+20 | 1.10E+20 | 9.30E+19 |
| 18 | Oil | 5.00E−02 mg/L | 1.63E+21 | 1.36E+21 | 1.05E+21 | 7.53E+20 | 5.18E+20 | 3.73E+20 | 3.50E+20 | 2.19E+20 |
| 19 | $NH_4$-N | 1.50E−01 mg/L | n.a. | n.a. | 0.00E+00 | n.a. | 1.06E+21 | 1.01E+21 | 1.21E+21 | 6.49E+20 |
| $R^*_{w-p-air}$ | Max(7:10) | | 1.25E+20 | 1.01E+20 | 7.35E+19 | 6.12E+19 | 5.50E+19 | 6.05E+19 | 4.67E+19 | 4.53E+19 |
| $R^*_{w-p-water}$ | Max(11:19) | | 1.63E+21 | 1.36E+21 | 1.05E+21 | 7.53E+20 | 1.06E+21 | 1.01E+21 | 1.21E+21 | 6.49E+20 |

Note: $R^*_{w-i}$: emergy of environmental services needed to dilute *i* pollutant to an acceptable level; p means pollutions from urban production, c means pollutions from urban use process.

*Indirect emergy input associated to emissions and ecological services*

Airborne emissions impacts on human health include respiratory disorders, climate change, etc. (Ukidwe and Bakshi, 2007). We considered six airborne pollutants ($SO_2$, dust, $NO_x$, $CO_2$, $CH_4$, $N_2O$) and eight waterborne pollutants (mercury, cadmium, hexavalent chromium, lead, arsenic, volatile phenol, cyanide, oil) as indicated in Fig. 5. Other pollutants were not considered for lack of sufficient data. From 1999 to 2006, the total human capital losses in urban use process caused by the six air pollutants increased dramatically from 4.17 x $10^{20}$ to 1.15 x $10^{21}$ seJ/year and reached a maximum peak of 1.31 x $10^{21}$ seJ/year in 2005, while losses due to the urban production sectors fluctuated with a maximum at 1.70 x $10^{21}$ seJ/year in 2005 as shown in Fig. 5(a) and (b). However, the total human capital losses caused by the urban production sector due to the six water pollutants investigated are much fewer than those caused by air pollutants (Fig. 5(c)), which indicates that emissions impacts, mainly fromair pollutants, are generally increasing from 1999 to 2006. As shown in Fig. 5(a), NOx and greenhouse gases ($CO_2$) take the largest share and the total value rises from 2.16 x $10^{20}$ seJ/year in 1999 to 6.23 x $10^{20}$ seJ/year in 2006.
The concentrations of NOx and dust have a large increase and jumpover $SO_2$ after 2003. In production sectors, as shown in Fig. 5(b), $CO_2$ and dust have the largest share.

A similar growth trend of $CO_2$ is shown by these two processes. The natural capital losses in urban production and consuming processes are illustrated in Fig. 5(d) and (e), which show that such losses, different from human capital losses, are assessed on the basis of acidification and ecotoxicologic emissions. The loss due to NOx demonstrates a very sharp increase in the investigated period, especially after 2004. Results suggest that $NO_2$ has overtaken $SO_2$ as the everbigger issue in Beijing's environmental pollution treatment during 1999–2006. The growth rate of damage that is caused by the emissions from urban consumption processes climbs up faster. Nitrogen dioxide and sulfur dioxide provided the largest contribution to natural capital loss while the greenhouse gases ($CO_2$) and dust play the larger role in human capital loss.

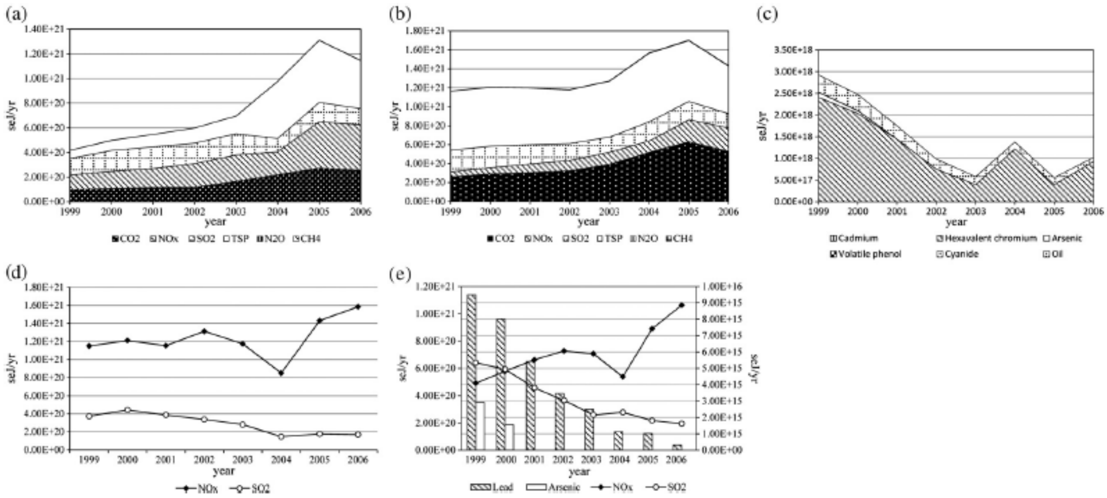



Fig. 5. The human capital and natural capital losses in urban socio-economic system caused by airborne and waterborne pollutants in 1999–2006. (a) The human capital losses in urban consumption processes caused by six air pollutants in 1999–2006; (b) the human capital losses in urban production processes caused by six air pollutants in 1999–2006; (c) the human capital losses in urban production processes caused by six water pollutants in 1999–2006; (d) the natural capital losses in urban production processes caused by selected air pollutants in 1999–2006; (e) the natural capital losses in urban production processes caused by both air and water pollutants in 1999–2006.

*Emergy investment for waste treatment*

We calculated the waste treatment emergy investment and feedback values for Beijing from 1999 to 2006 and the results are summarized in Table 4. Due to the uncertainty of available data, the exact losses without waste treatment processes are difficult to estimate. Here, a rough estimate is provided based on the ratio of waste elimination after the treatment (the hypothesis is made that the concentration of selected pollutants in waste can be reduced by 80% after treatment).

Based on these results, emergy investment in the waste treatment shows a relatively stable increasing trend during the eight years, even though it goes through some fluctuations and inversions. $F_b$ appears to be low, amounting to about 2%–5% of the emergy investment for treatment, but increases with years going on. $L_{w,i}/L^*_{w,i}$ can illustrate the coupling relationship between the emissions influence and the treatment effect. $L_{w,1}$ can only increase by 275% so that untreated pollutions, $CO_2$ and dust, take the largest share in human losses. Hypothesis-based results show that the total emergy input is much less than losses reduction. However, there is a non-synchronized growth with the emergy investment and losses reduction. Results suggest that in virtually all cases there is no single "optimal" solution by enlarging the investment to the pollutions control, which resembles the marginal pollution damage curve proposed by Jaffe et al. (2003) and Requate (2005) after surveying the literature on pollution control and endogenous investment. The emergy loss associated with land occupation can be used as a measure of the environmental impact of discharged solid waste. Such an emergy loss caused by solid waste increased significantly during 1999–2006 (Table 5). Therefore, the reduction of the amount of discharged solid waste is a serious issue for Beijing.

**Table 4**
The additional emergy input for waste treatment and loss reduction (sej/year).

| | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 |
|---|---|---|---|---|---|---|---|---|
| $E_w$ | 1.33E+21 | 1.52E+21 | 1.62E+21 | 1.99E+21 | 2.37E+21 | 2.85E+21 | 2.73E+21 | 3.24E+21 |
| $F_b$ | 2.35E+19 | 2.68E+19 | 3.19E+19 | 5.35E+19 | 8.15E+19 | 1.17E+20 | 1.45E+20 | 1.31E+20 |
| $R_w/R_w^*$ | 500% | | | | | | | |
| $L_{w,1}/L_{w,1}^*$ | 275% | | | | | | | |
| $L_{w,2}/L_{w,2}^*$ | 500% | | | | | | | |
| Losses reduction | 1.34E+22 | 1.43E+22 | 1.37E+22 | 1.41E+22 | 1.31E+22 | 1.17E+22 | 1.61E+22 | 1.65E+22 |

**Table 5**
The emergy losses caused by the solid pollutants (sej/year).

| | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 |
|---|---|---|---|---|---|---|---|---|
| $L_{w,3\text{-}p}$ | 6.42E+18 | 7.69E+18 | 8.51E+18 | 8.44E+18 | 1.08E+19 | 1.48E+19 | 1.63E+19 | 1.69E+19 |
| $L_{w,3\text{-}c}$ | 8.10E+18 | 1.09E+19 | 1.32E+19 | 1.46E+19 | 2.06E+19 | 3.23E+19 | 4.13E+19 | 4.51E+19 |

Note: p means pollutions come from urban production, c means pollutions come from urban use process.

*Integrated analysis of Beijing based on emergy indicators*

For the purpose of exploring the trend of Beijing sustainability dynamics during its recent economic growth, a whole set of emergy performance indices were calculated as indicated in Table 6. The reliance of a process on local resources can be revealed by the emergy yield ratio (EYR). Only a balanced rate of free local resources and imported resources may ensure the sustainable development of a city. Table 6 clearly shows that the fast growth of the city is accompanied by a decrease of its emergy yield ratio in the years from 1999 to 2006, suggesting that Beijing increasingly relied on resources imported from outside. After the indirect emergy input associated with the impact of emissions was accounted, the yield ratio, EYR′, was slightly smaller than the previous EYR, due to an increased use of imported resources. The yield ratio decrease was not, however, very large, because of the fact that imported resources were already much more than local ones, so that the increased emergy demand was not important in relative terms. The environmental loading ratio, ELR, declined rapidly from 34.8 in 1999 to 25.4 in 2005 after the implementation of the Reform and Opening-up Policy, which reflected that although Beijing growth was accompanied by a very large environmental pressure on local resources, the emissions had been effectively controlled. The small increase in 2006 might be attributed to an oscillation of the growth trend and cannot be interpreted until new data for the following years are available. The loading ratio further increased (ELR′) after considering the additional emergy demand for emissions' impacts, since the indirect input flows were mainly non-renewable emergy. As a consequence of EYR, EYR′, ELR, and ELR′ trends, the ESI and ESI′ values also change accordingly. Due to the combined effect of the decreased yield ratio (EYR′<EYR) and increased loading ratio (ELR′> ELR), the sustainability index ESI′ dropped significantly, thus suggesting that emissions greatly reduced the sustainability of the urban system by pulling resources for damage repair and for replacement of lost natural and human-made capital.

**Table 6**
Summary of flows of the city 1999–2006.

| Variable | Unit | Item | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 |
|---|---|---|---|---|---|---|---|---|---|---|
| $R$ | seJ/year | Renewable sources | 1.05E+21 | 1.05E+21 | 1.05E+21 | 1.05E+21 | 1.03E+21 | 1.03E+21 | 1.03E+21 | 1.03E+21 |
| $N$ | seJ/year | Nonrenewable resources, $N=N_0+N_1$ | 1.69E+22 | 1.18E+22 | 1.47E+22 | 1.88E+22 | 1.75E+22 | 1.94E+22 | 2.01E+22 | 1.37E+22 |
| $N_0$ | seJ/year | Dispersed rural source | 3.90E+19 | 3.90E+19 | 3.90E+19 | 3.90E+19 | 3.90E+19 | 3.90E+19 | 3.90E+19 | 3.90E+19 |
| $N_1$ | seJ/year | Concentrated use | 1.68E+22 | 1.18E+22 | 1.47E+22 | 1.87E+22 | 1.75E+22 | 1.93E+22 | 2.01E+22 | 1.37E+22 |
| $G$ | seJ/year | Imported goods | 5.20E+22 | 7.45E+22 | 8.68E+22 | 1.01E+23 | 1.21E+23 | 1.51E+23 | 1.73E+23 | 1.89E+23 |
| $F$ | seJ/year | Imported fuels | 9.94E+22 | 1.07E+23 | 1.10E+23 | 1.07E+23 | 1.18E+23 | 1.36E+23 | 1.50E+23 | 1.60E+23 |
| $P_2I$ | seJ/year | Purchased services | 5.05E+22 | 7.28E+22 | 7.63E+22 | 8.37E+22 | 1.13E+23 | 1.38E+23 | 1.70E+23 | 2.02E+23 |
| $P_2I_2$ | seJ/year | Emergy for tourism | 4.46E+22 | 5.52E+22 | 6.85E+22 | 7.17E+22 | 5.21E+22 | 8.50E+22 | 9.74E+22 | 1.15E+23 |
| $P_2I_3$ | seJ/year | Emergy paid for imported labor | 6.62E+20 | 9.43E+20 | 1.29E+21 | 1.44E+21 | 1.87E+21 | 2.33E+21 | 3.65E+21 | 3.65E+21 |
| $(P_2I+P_2I_3)_R$ | seJ/year | Renewable fraction (10%) | 5.12E+21 | 7.37E+21 | 7.76E+21 | 8.51E+21 | 1.15E+22 | 1.40E+22 | 1.74E+22 | 2.06E+22 |
| $(P_2I+P_2I_3)_N$ | seJ/year | Non-renewable fraction (90%) | 4.60E+22 | 6.64E+22 | 6.98E+22 | 7.66E+22 | 1.03E+23 | 1.26E+23 | 1.56E+23 | 1.85E+23 |
| $U$ | seJ/year | $U=R+N+G+F+P_2I+P_2I_3$ | 2.21E+23 | 2.68E+23 | 2.90E+23 | 3.13E+23 | 3.72E+23 | 4.48E+23 | 5.18E+23 | 4.69E+23 |
| POP | | Population | 1.26E+07 | 1.36E+07 | 1.38E+07 | 1.42E+07 | 1.46E+07 | 1.49E+07 | 1.54E+07 | 1.58E+07 |
| GDP | $/year | Gross domestic product | 2.63E+10 | 3.00E+10 | 3.45E+10 | 3.88E+10 | 4.43E+10 | 5.17E+10 | 8.41E+10 | 1.01E+11 |
| $R_w^*$ | seJ/year | Emergy of ecological services needed to dissipate the emissions | 2.63E+22 | 5.19E+22 | 4.91E+22 | 4.99E+22 | 4.43E+22 | 1.90E+22 | 1.60E+22 | 1.42E+22 |
| $L_{w,1}^*$ | seJ/year | Emergy of the human life losses caused by the emissions | 1.59E+21 | 1.71E+21 | 1.75E+21 | 1.78E+21 | 1.97E+21 | 2.55E+21 | 3.02E+21 | 2.58E+21 |
| $L_{w,2}^*$ | seJ/year | Emergy of the ecological losses due to the emissions | 2.65E+21 | 2.82E+21 | 2.66E+21 | 2.74E+21 | 2.42E+21 | 1.81E+21 | 2.71E+21 | 3.01E+21 |
| $L_{w,3}$ | seJ/year | Emergy of the land occupation caused by the emissions | 1.21E+19 | 1.54E+19 | 1.76E+19 | 1.87E+19 | 2.75E+19 | 3.96E+19 | 4.84E+19 | 4.98E+19 |
| $U_w$ | seJ/year | Emergy investment for waste treatment | 1.33E+21 | 1.52E+21 | 1.62E+21 | 1.99E+21 | 2.37E+21 | 2.85E+21 | 2.73E+21 | 3.24E+21 |
| $F_b$ | seJ/year | Feedback emergy | 2.35E+19 | 2.68E+19 | 3.19E+19 | 5.35E+19 | 8.15E+19 | 1.17E+20 | 1.45E+20 | 1.31E+20 |
| EYR | | $U/(G+F+P_2I+P_2I_3)$ | 1.09E+00 | 1.05E+00 | 1.06E+00 | 1.07E+00 | 1.05E+00 | 1.05E+00 | 1.04E+00 | 1.03E+00 |
| EYR′ | | $(U+R_w^*+L_{w,1}^*+L_{w,2}^*+L_{w,3}-F_b)/(G+F+P_2I+P_2I_3+R_w^*+L_{w,1}^*+L_{w,2}^*+L_{w,3}-F_b)$ | 1.08E+00 | 1.04E+00 | 1.05E+00 | 1.06E+00 | 1.05E+00 | 1.05E+00 | 1.04E+00 | 1.03E+00 |
| ELR | | $(N+G+F+(P_2I+P_2I_3)_{RN})/(R+(P_2I+P_2I_3)_R)$ | 3.48E+01 | 3.08E+01 | 3.19E+01 | 3.17E+01 | 2.88E+01 | 2.87E+01 | 2.71E+01 | 2.54E+01 |
| ELR′ | | $(N+G+F+(P_2I+P_2I_3)_N+R_w^*+L_{w,1}^*+L_{w,2}^*+L_{w,3}-F_b)/(R+(P_2I+P_2I_3)_R)$ | 3.97E+01 | 3.75E+01 | 3.80E+01 | 3.74E+01 | 3.26E+01 | 3.03E+01 | 2.83E+01 | 2.63E+01 |
| ESI | | EYR/ELR | 3.14E−02 | 3.41E−02 | 3.32E−02 | 3.37E−02 | 3.65E−02 | 3.66E−02 | 3.83E−02 | 4.06E−02 |
| ESI′ | | EYR′/ELR′ | 2.72E−02 | 2.77E−02 | 2.76E−02 | 2.83E−02 | 3.22E−02 | 3.47E−02 | 3.67E−02 | 3.92E−02 |

*Conclusion*

This research focused on the Beijing urban socio-economic system based on emergy synthesis, integrated with the environmental impact assessment models under the framework of the Eco-Indicator 99, in order to highlight the emergy loss generated by emissions and include it as an additional cost to be charged to the socio-economic system. The emergy values of human-made and natural capital lost were considered as indirect inputs of ecological services for airborne and waterborne pollutants dilution and damage repair or replacement. This approach provided important insights to the understanding of the relationship between emission environment impact and urban system. Detailed trends of the resource base and performance indicators are examined in a historical perspective for the contemporary Beijing urban systemafter China's Economic Reform and Opening Policies in the latest decade.

Results showthat emissions' impacts, mainly from air pollutants, are generally increasing from 1999 to 2006 and they obviously affect the sustainability in Beijing. Air pollutants control, especially greenhouse gases andnitrogen oxide emission control in useprocess, should be more emphasized in future, but the additional investment needed suggests prevention instead of end-of-pipe treatment strategies. Wise environmental policy making should therefore integrate the emergy synthesis method (supply-side perspective) and the environmental impact assessment models according to the framework of the Eco-Indicator 99 in order to fully understand and quantify the real cost of a sustainable production and consumption strategy based on a comprehensive account of both source and sink sides of economic growth.

Since emergy analysis is based on a single common inventory of all the system's inputs and outputs, the systematic uncertainties are simultaneously performed on all calculated data and indicators, simply by allowing for variable cells for all input quantities as well as for the associated impact coefficients (intensity factors) in the spreadsheet-based calculation procedures. Quantifying direct and indirect flows of matter and energy to and from a system permits the construction of a detailed picture of the process itself as well as of its relationship with the surrounding environment. Ingwersen (2010) attempted to describe sources of uncertainty in unit emergy values (UEVs) and presents a framework for estimating this uncertainty with analytical and stochastic models, with model choices dependent upon on how the UEV is calculated and what kind of uncertainties are quantified. However, in practice, describing the uncertainty in parameters, scenarios and models requires significant effort and must draw from previous applications of various models and across various scenarios (Ingwersen, 2010). However, the data of uncertainty for each UEV, especially the complex products and wastes, was not readily available. Thus, uncertainty analysis will be considered along with inventory uncertainty data to calculate uncertainty in estimates of total emergy in complex life cycles in the future work after achieve the uncertainty analysis of the LCA inventory.

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# CHAPTER 11. ENERGY EFFICIENCY AND STAKEHOLDERS

### *11.1 Introduction*

The most important reason to recommend energy efficiency is that it has the greatest potential to limit future energy demand and face energy shortages. The International Energy Association (IEA) estimates that the global demand for energy may increase by 35% by the year 2035 (IEA, 2012). However, worldwide economies are not fully exploiting the potential of energy efficiency activities to save energy for the future generations (IDFC – 2014).

IEA estimates that energy efficiency may account for as much as 70% of the reduction in global energy demand, assuming that nations keep recent commitments to energy efficiency policies (IEA 2012). Most Governments have implemented a wide range of policies and programmes to accelerate the development and adoption of energy efficiency measures.

Energy efficiency advocates also argue that efficiency improvements can provide social benefits such as increased productivity and employment, reductions in the high-energy cost burden faced by low-income households, improved comfort and public health, enhanced national security, and conservation of finite resources such as oil and natural gas (Romm 1999; Jochem 2000; Geller 2003). For this reason, it is important to engage all the stakeholders and make them the main actors of these policies and programmes.

Many countries use a strategy development or action planning process as a means to engage stakeholders, build consensus and activate action on energy efficiency. These strategies and action plans help guide and encourage energy efficiency policy development and implementation by: *placing energy efficiency policy within the broader policy context; allocating resources across the range of possible energy efficiency policies; capturing synergies between policies; engaging stakeholders and building political consensus; and assigning responsibility for policy development, implementation and oversight* (IEA, 2009b).

National energy efficiency strategies play an important role as they provide a high-level overview of how a country can meet economy-wide goals. The European Union's 20-20-20 target aims for a 20% reduction in primary energy use compared with projected levels by 2020. An energy efficiency strategy should also be comprehensive in describing the approach to and rationale for energy efficiency policies and programmes.

In this chapter, we aim to better understand and describe what stakeholders think about energy efficiency and how they can likely deal with it.

### *11.2 Methods*

#### 11.2.1 Stakeholder Mapping

Stakeholder mapping is based on four pillars:

1. Define stakeholders;
2. Analyse stakeholders by impact and influence;
3. Plan Manage stakeholder communications and reporting;
4. Engage with stakeholders.

A stakeholder is anybody who can affect or is affected by an organization, strategy or project. They can be internal or external and they can be at senior or junior levels. Some definitions suggest that stakeholders are those who have the power to impact an organisation or project in some way and they might change the implementation of a certain project that could have a negative effect on their stake. Defining stakeholders is the first important step for a future stakeholder engagement.

After an overview of all the possible stakeholders who play a role in the analysed situation it is possible to define the influence, the impact and the importance of these persons in the area. It is important to understand their level of influence and importance because it will be easy to understand how to interact and communicate with them, depending on their level of membership. After these two steps, it is necessary to plan communications between stakeholders in order to improve their engagement and manage the conflicts.

Stakeholder analysis is a methodology used to facilitate institutional and policy reform processes by accounting for and often incorporating the needs of those who have a 'stake' or an interest in the reforms taken into consideration. Stakeholder Analysis was born from the business sciences, but as it developed it came to include economics, political science, game and decision theory and environmental sciences. Actually, the models of Stakeholder Analysis adopt a variety of tools on both qualitative and quantitative data to understand stakeholders, their positions, influence on other groups, and their interest in a particular reform. The stakeholder analysis and stakeholder mapping are strongly connected and both of them are used when it is necessary to manage a situation with different stakeholder involved.

#### *11.2.2 An energy-efficiency questionnaire*

An energy-efficiency oriented questionnaire was sent to a group of around 200 selected stakeholders from October 2016 and the consultation was stopped at the end of the year.

We received 83 replies. The aim of this consultation was to understand the level of engagement of stakeholders on energy efficiency and their knowledge about this issue.

The questionnaire was composed with 29 questions, some of which general questions about energy efficiency and stakeholder's behaviour and some more technical, linked to the EUFORIE project.

The first set of questions were meant to investigate what stakeholders think about energy efficiency and what they know about it. In the second part, we also tried to assess their present engagement or how they could be engaged in the future. Questionnaire were proposed by means of personal interviews, contacts during specialized meetings and online compilation. In several questions respondents were asked to mark more than one answer. For this reason, the sum of achieved percentages most often overcomes 100%.

### *1.3 Results*

Figure 11.1 deals with the definition of the energy efficiency concept. The majority of respondents (83,30%) show a lifestyle-oriented definition of the concept, aiming at consuming less and spending less, without decreasing the quality of life. This points out what is the most important result to be achieved, namely providing technologies and organization forms that do not affect the present living standard. Very likely policies that force lifestyles to decrease would not meet stakeholders' acceptance.

The need for additional information about energy efficiency seems a crucial issue also in the minds of stakeholders. For this to be achieved, they identify the need to spread the concept via media (66.7%), schools (55.6), public offices (55.6) that act as contacts for stakeholders, promotion activities. This would certainly require a planned strategy by policy-makers and an investment of resources. Surprisingly, self-managed tools such as "social networks" are not considered a potential solution, very likely due to the need for expert advice, that stakeholders attribute to Institutional planning and intervention. (Figure 11.2). Stakeholders think that it is important to inform more people, on the media (66,70%) or in the schools (55,60%), or to open some offices in charge to inform about the exsting energy efficiency solutions (55.60%) or to promote the concept through events, contests or other ways (55.60%).

In fact, lack of information was identified as the main barrier to the implementation of energy efficiency by all respondents, together with insufficient action by public administration (Figure 11.3): the latter is considered the second most important barrier (61,1%), followed by some confusion between energy efficiency and renewable energy (38,9%), lack of financing tools (33.3%), lack of technological skills (16,7%) and lastly the idea that in Italy we have other more urgent needs to take care of, instead of talking about energy efficiency (11,1%). Surprising, stakeholders attribute a small importance to the technical aspects (considered not to be a barrier) and the financial aspects (likely the existing incentives are considered sufficiently attractive).

The possibility to save money is not the only solution that governments should consider to reduce consumption. Figure 11.4 shows that 72% of respondents think that incentives are not the only way, although all of them agree that they are a good starting point to support effective changes in stakeholders' behaviours. Concerning stakeholders' awareness about Italian subsidies and regulations regarding the energy efficiency matter, Figure 11.5 points out that the 55.6% of respondents declare to be aware of the financial aids provided by the Italian government, and the 44,4% of stakeholders think they only know a part of them, in this case respondents could trace one answer. Going into further details, we explored to what extent stakeholders were informed of some specific incentives.

A question about tax reductions related to actions to improve the efficiency in buildings and houses lead to 88.9% of respondents declaring to be fully informed while only 11.1% appeared not informed (Table 11.1, questions 1), further confirmed by answers to question 3, related to other incentiving measures and regulations; in the same Table, the question No. 2 explores the availability to invest personal sources of funding to improve the energy efficiency of the apartment yielding about 80% of answers in favour of such action, depending on the solutions to be adopted. These results might suggest that people are becoming more aware of energy efficiency options and that they care about the possibility to implement energy saving strategies and tools by using the available tools.

**Table 11.1 - Subsidies and tax deduction**

| | | | |
|---|---|---|---|
| ***1. Are you aware of the possibility of the tax deduction of 65% for measures to improve energy efficiency and seismic upgrading of buildings, recoverable in 10 years?*** | | **Yes** | **I heard about it and I may do something in the future** |
| | | 88,9% | 11,1% |
| ***2.Would you invest a sum of your personal budget to adapt your home and*** | **Yes** | **It depends on the extent of benefits** | **It depends on the budget I need to spend** |

| | | | |
|---|---|---|---|
| ***become more efficient?*** | 38,9 % | 38,9 % | 22,2% |
| ***3. Are you aware of other regulations and incentives for energy efficiency in Italy, a part from tax deduction?*** | | **Yes** | **Yes, but not well informed about** |
| | | 55,6% | 44,4% |

When asked about so-called White Certificates (Energy Efficiency Certificates – EEC, Table 11.2, question 4) - a proof of the energy savings achieved through energy efficiency improvement initiatives and projects - stakeholders declared to be well informed about them. When asked about ESCo's (Energy Service Companies, Table 11.2, question 5) the majority said they knew them (83,3%), some of them did not know anything (11,1%), just a few heard about them but did not know any details (5,6%). Such claimed awareness of the existing technical tools for an energy efficiency market is not fully in agreement with the daily experience of ESCo's, as it emerges from our strict collaboration with them (in particular with FEDERESCO, the Italian Federation of ESCo's, http://www.federesco.org/en/). These energy efficiency companies suffer from several regulatory delays and small market acceptance, which calls for increased governmental regulation, promotion and support of the energy efficiency matter, market and actors.

Another general question explored how stakeholders were informed about energy efficiency (in order to understand the most effective sources of information). Figure 11.6 indicates that the 61,1% of respondents refer to technical documents for professional reasons: this percentage might depend on the fact that the questionnaire was also sent to experts and people who work in this field or in environmental organizations; social networks and newspaper got the same score, 11,1%, and the answer "other" was indicated by 16,7% of respondents.

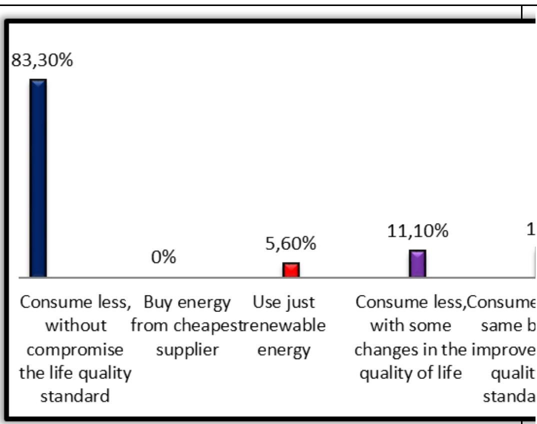



Figure 11.1 – What does Energy Efficiency mean?

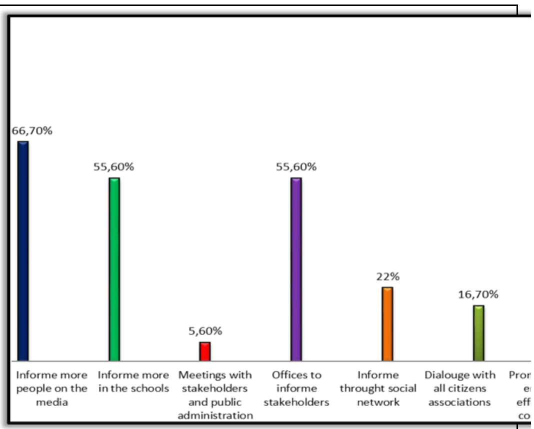



Figure 11.2 – How to promote the energy efficency concept ?

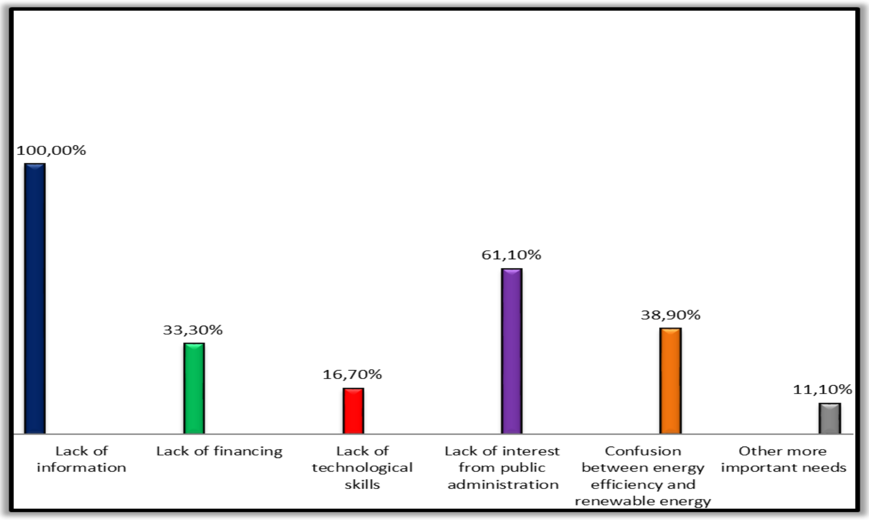



Figure 11.3 – What are the main barriers to energy efficency ?

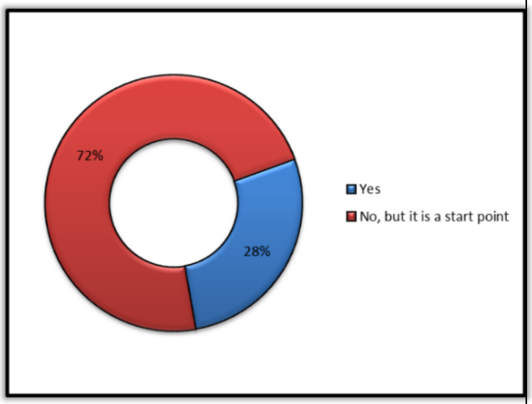



Figure 11.4 – Are subsidies and incentives the only solution to achieve energy efficiency?

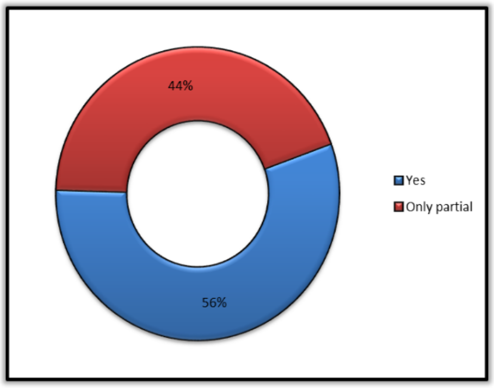



Figure 11.5 – Are you aware of the existence of subsidies and incentives within the Italian regulations ?

**Table 11.2 - ESCo's and White Certificate**

<table>
<tr><td rowspan="2" colspan="2">4. Do you know what White Certificates are?</td><td>Yes</td><td colspan="2">No</td></tr>
<tr><td>84 %</td><td colspan="2">16,7 %</td></tr>
<tr><td rowspan="2">5. Do you know what does ESCo mean?</td><td>Yes</td><td>No</td><td colspan="2">I heard about it, but I don't know much</td></tr>
<tr><td>83,3 %</td><td>10 %</td><td colspan="2">6,4%</td></tr>
</table>

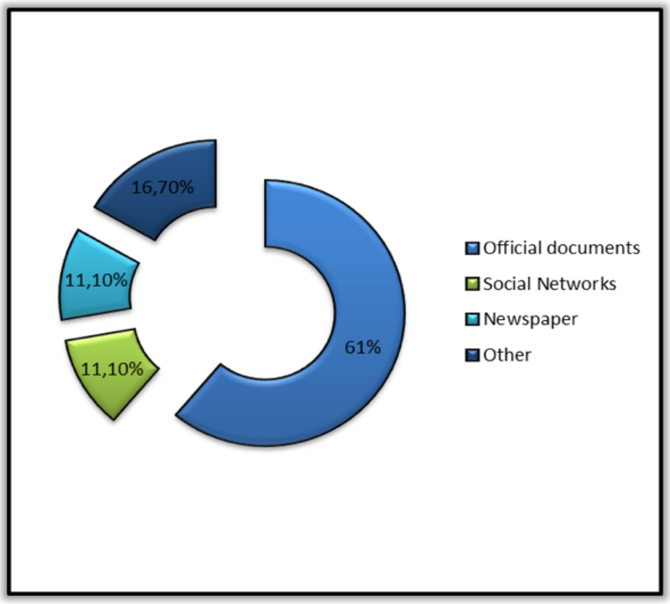



Figure 11.6 – Where did you find information about energy efficiency ?

After these general questions, additional focus was placed on stakeholders' participation and the possibility to get them involved in some decision-making process. The Figure 11.7 is a roadmap, developed within the Parthenope research team, with the main elements, steps and interactions of a decision-making toolkit based on an integrated approach. The application of the decision-making roadmap is expected to provide sufficient technical and social evaluation indicators that may allow conflict prevention and final implementation. It seems clear that participatory decision-making approaches need to start from a real demand for specific services and then develop towards the optimum solution (or optimum compromise) through a series of technical details transparently made available, discussed, evaluated across a variety of points of view and finally accepted or rejected.

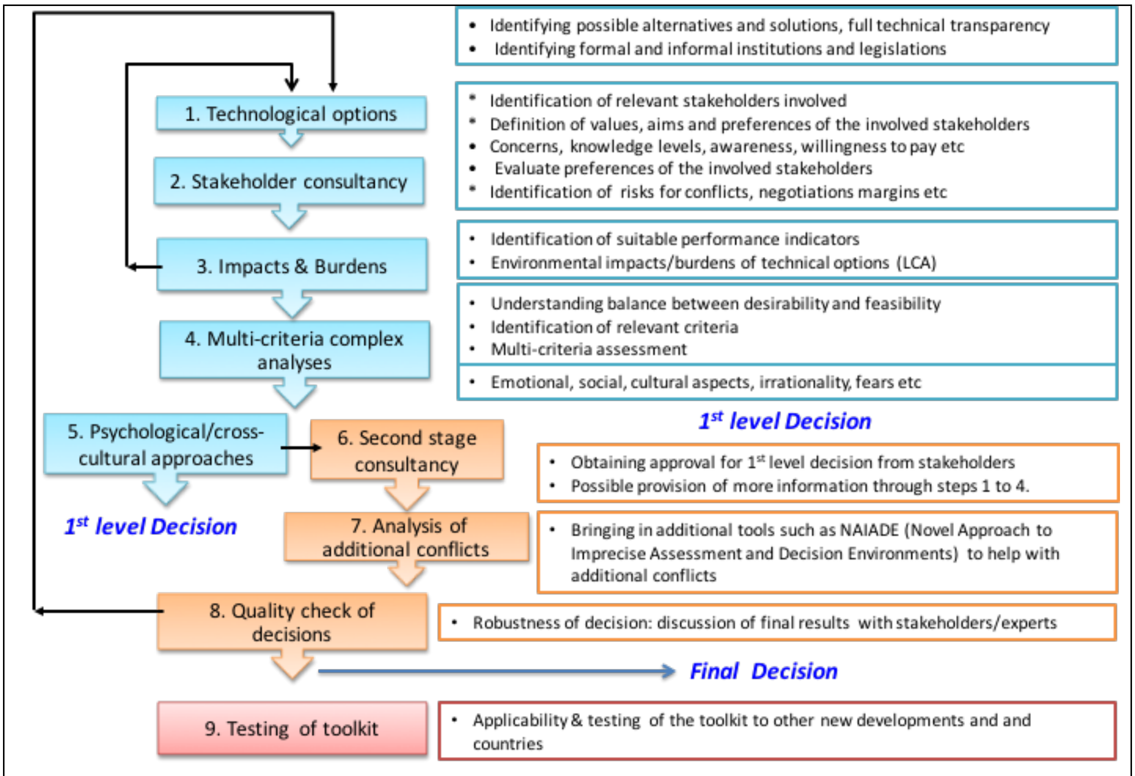


Figure 11.7 – Participatory decision-making roadmap

We made the roadmap scheme of Figure 11.7 available to the interviewed stakeholders and asked them if the roadmap was sufficiently clear and which were the most important steps of the participatory process in their opinion. Stakeholders identified the conflict analysis of the different "stakes" (Step 2) as one of the most important steps for this process (44,4%) and pointed out that in general stakeholders should always be involved (33,3%).

Then we kept on asking questions about the engagement of stakeholders in the participatory process, their level and extent of engagement and their availability to get involved in the process personally. Questions 6 and 7 of Table 11.3 express the stakeholders' trust of the participatory process, pointing out the importance of defining carefully the steps of the participatory process and the interests of the different stakeholders. This is a very important point: if interests and procedures are well defined and transparent, the risk for hidden interests and conflicting decisions is decreased. The largest majority of stakeholders would appreciate being involved in the decision-making process (Table 11.3, question 8) and the reason is not, as it might be inferred, that they do not trust policy-makers (question 9), but more than that stakeholders think that they may be able to provide points of view and solutions that experts and policy-makers will hardly notice. However, stakeholders identify meetings as the best tool to participate, which is a clear signal of availability to get involved personally in the roadmap and the process.

**Table 11.3 - Stakeholders' Engagement**

| | | | | |
|---|---|---|---|---|
| ***6. About roadmap, do you think that participation process could help the harmonization of interests of different stakeholders involved?*** | **Yes, but each part of the participatory process must be defined** | **Maybe, changing some part of the roadmap** | **Yes** | **I don't think so** |
| | 43 % | 33,3% | 16,7% | 12 % |
| ***7. Do you think it is important to consult all the stakeholders involved, or just the experts that might help public administration to take decision*?** | **Public administrations have to listen all the stakeholders involved** | **Just experts must help public administrations** | **Even if it is complicated, everybody must be involved** | |
| | 38,9% | 35 % | 22,2 % | |
| ***8. Would you like to be involved in decision making related to the problems of your city?*** | **Yes** | **No, I prefer that just experts think about these problems** | | |
| | 77,8 % | 17 % | | |
| ***9. Why would you like to be involved in the problems of your city?*** | **Because to change situations everybody has to give their contribution** | **Because for some problems we don't need just technological solutions** | **Because I don't trust public administration** | |
| | 40% | 29 % | 26,7 % | |
| ***10. Would you like to participate to meetings on energy efficiency?*** | **Yes** | **It depends on the meetings** | **No, I prefer to get informed in other ways** | |
| | 77,8 % | 17,3 % | 7,8% | |

After exploring the issue of roadmap implementation and stakeholders' involvement, we enquired about the possibility to promote this way of taking decision and who should be the principal actors in this process.

Figure 11.8 presents the different answers: the 72,2% of stakeholders said public administration, 50% said all together, each one with his personal capacity, the 38,9% of respondents think the public administration that are in charge of a particular problem, 16,7% technical experts and 5.6% said citizens. The meaning is clear: in spite of claimed lack of trust in administrators, yet stakeholders assign to Istitutions and experts the main role to promote a participatory process. This means that institutional roles are not void of importance to the eyes of stakeholders.

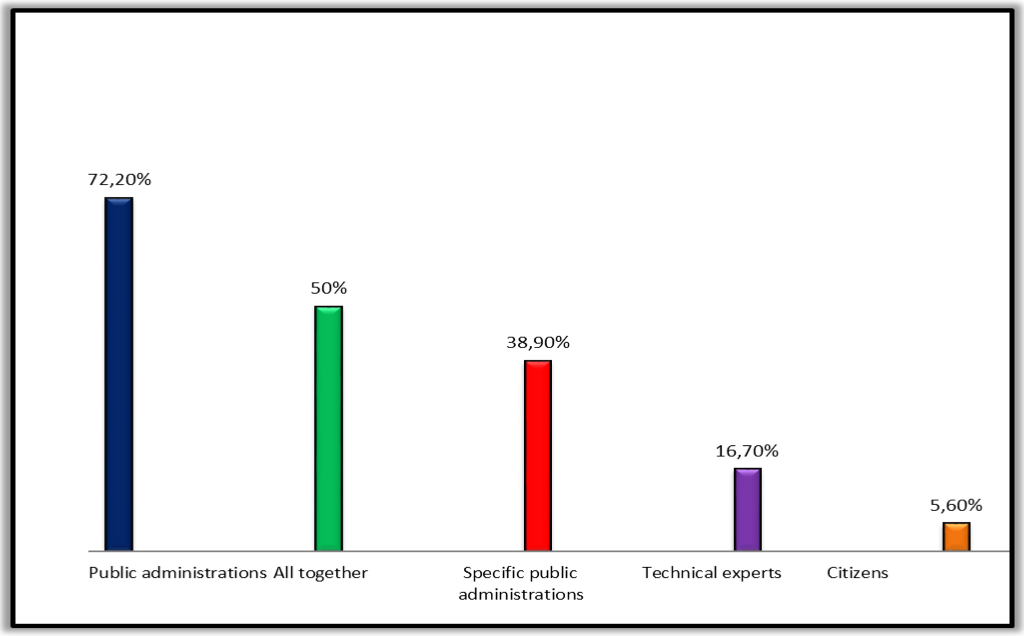



Figure 11.8 – Who should promote participatory process?

After the above questions about participation and stakeholders engagement, the second part of the questionnaire is more strictly linked to the EUFORIE project.

A preliminary survey of what stakeholders consider "energy efficiency" and what are their daily actions (Table 11.4) provides very telling informations. Stakeholders look at a mix of technical solutions (thermal insulation, more efficient appliances) and lifestyle changes (reduction of waste, increased use of public transportation). Their preference to photovoltaic and thermal solar devices is expressed, but correctly the majority of respondents does not consider them as a form of energy efficiency.

**Table 11.4 - Concept of Energy Efficiency and daily life habits**

| *11. Which one of the following options characterizse the concept of energy efficiency in your opinion?* | **Windows' thermal insulation** | **Ceiling and Walls' thermal insulation** | **Intensify Public transportation use** | **Change lifestyle and reduce food waste** | **Purchase class A + appliances** | **Solar modules for electricity and water heating** |
|---|---|---|---|---|---|---|
| | 55,6 % | 50 % | 44,4 % | 38,3 % | 27,8% | 11,8 % |
| ***12. Which one of the following options do you already adopt in your daily life?*** | **Windows' thermal insulation** | **Change lifestyle and reduce food waste** | **Intensify Public transportation use** | **Purchase class A + appliances** | **Ceiling and Walls' thermal insulation** | **Solar modules for electricity and water heating** |
| | 50 % | 57,3 % | 55,4 % | 43,8 % | 11,1% | 9,6 % |

As a practical way to address aspects of energy efficiency and be personally involved, the Parthenope University invited the local stakeholders in Napoli to give rise to the so-called Urban Wellbeing Laboratories, i.e. monthly meetings among environmental associations, professors and researchers, students, professionals and administrators, in order to stress topics of interest for the city separatedly from the need to take decisions immediately. This kind of preventive action was very well accepted (Table 11.5, question 13) and the motivations, once again, were not the lack of reliability of public authorities, but instead the willingness to contribute and the hope to decrease the conflicts (Table 11.6, question 14).

**Table 11.5 - Urban wellbeing laboratories**

| ***13. Do you think that Wellbeing Laboratories could be useful to discuss the problems of your cities?*** | **Yes** | **Maybe, but we should do something practical, not just talk about problems** | **Yes, but University shouldn't be the promoter of the Laboratories** |
|---|---|---|---|
| | 50% | 36% | 17,6 % |

**Table 11.6 - Motivations behind stakeholders' involvement**

| *14. Do you think that today stakeholders' involvement is more important because public authorities are not reliable?* | It is not because they are not reliable, but because every stakeholder has to be involved in public decision making | Stakeholders' involvement reduce conflict and increase social wellness | Others |
|---|---|---|---|
| | 50% | 41% | 11,3 % |

After these more general questions, we raised a number of specific, very detailed questions mainly about technical aspects (Tables 11.7 to 11.12). These Tables are very telling concerning specific choices, preferences, knowledge.

In each question, we asked to provide a grade from 1 to 10 to the different items, in order to understand how the most important tools and strategies might become more efficient and effective. Questions in Tables 11.7 to 11.12 should be read in the light of previous answers in Tables 11.1, 11.4 and Figures 11.1 to 11.5 as well as Figure 11.8. These previous Figures set the stage for understanding the relation between general policy aspects and specific implementation actions. Stakeholders assign higher grades to those actions that they find more useful or where they identify the existence of barriers.

Accurate consideration of the entire set of stakeholders answers and availability to contribute may provide a god starting point to assess future energy efficiency policies. Perspectives, desires and policies will have to be compared to energy, environmental costs and life cycle impacts assessed in previous Chapters 1 to 10 as well as following Chapters 12 and 13. For the sake of clarity and help reading Tables 11.7 to 11.12, we have highlighted in bold the largest percentages of stakeholders for the grades assigned to specific energy efficiency measures, as a proof of consensus in judging that measure. For example, issuing "laws and regulations" was considered a good measure (grade: 8) by 30% of responses. Other responses indicated a lower ranking, also characterized by lower consensus. Instead, measures to improve "awareness and behavioural patterns" were judged of intermediate quality and effectiveness (grade: 6) by 81% of responses, in so underlining the limited consensus on these measures. We may therefore judge the quality of measures, by cross-checking responses and percentages.

Once consensus is monitored, policies may be based on a mix of the most accepted measures, or efforts might displayed to explain the less accepted measures and try to change the behaviour of stakeholders.

**Table 11.7 – Main energy efficiency measures implemented in Italy and Europe (grades from 1 to 10, 1 less important – 10 really important)**

| **Grades** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| Regulatory Actions: Laws | - | - | - | - | 25% | 11% | 9% | **30%** | - | - |
| Reduce Energy Imports | 7% | - | - | - | 11% | 21% | - | **22%** | - | 8% |
| Increase environmental quality and reduce pollution | - | - | - | - | - | 17% | - | **83%** | - | 10% |
| Reduce Energy Costs | - | 5% | - | 13% | - | **33%** | 15% | - | - | 3% |
| Energy Service Pric | - | - | - | 4% | - | 18% | **72%** | - | - | - |
| Increase the proportion of renewable energy | - | - | 8% | - | - | **40%** | 39% | - | - | - |
| Environmental protection challenges | - | 3% | - | 2% | 11% | 5% | 21% | - | **56%** | - |
| Social and cultural pressure | - | - | - | - | - | - | 29% | **43%** | 26% | 17% |
| Awareness and behavioral patterns | - | 4% | - | - | - | **81%** | - | 22% | 31% | 2% |
| Laws and regulation | - | - | - | - | - | 36% | **74%** | - | - | - |
| Increase in real estate value | - | - | - | - | - | **47%** | 36% | 29% | - | - |
| Governments' helps to reduce energy consumption | - | - | 3% | - | - | - | 49% | **51%** | - | - |

**Table 11.8 Factors that could help Energy Efficiency Implementation (Grades from 1 to 10, 1 less important – 10 really important)**

| Grades | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Energy Availability | - | - | - | - | - | - | 41% | 28% | 15% | 7% |
| Reduce Energy Importation | 4% | 3% | - | - | 11% | - | 31% | 36% | 41% | 6% |
| Increase environmental quality and reduce pollution | - | - | 5% | 7% | - | 13% | - | 63% | - | 14% |
| Reduce Energy Costs | 2% | - | - | 13% | - | - | - | 26% | 42% | 8% |
| Energy Service Price | - | - | - | - | 3% | - | 45% | 31% | 18% | 18% |
| Increase the proportion of renewable energy | - | - | - | - | - | - | 21% | - | 33% | - |
| Environmental protection challenges | - | 2% | - | 20% | 61% | 50% | - | - | 22% | 36% |
| Social and cultural pressures | - | - | - | - | - | 15% | 29% | 43% | 26% | 17% |
| Awareness and behavioral patterns | - | 4% | - | - | - | 41% | - | 62% | - | 11% |
| Laws and regulations | - | 5% | - | - | - | - | 26% | - | - | - |
| Increase in real estate value | - | - | - | - | - | - | 41% | 16% | - | - |
| Governments' helps to reduce energy consumption | - | - | - | - | - | - | 9% | 35% | 26% | - |

**Table 11.9 - Energy Efficiency Policies**

**(Grades from 1 to 10, 1 less important – 10 really important)**

| Grades | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Energetic Audit | - | - | - | - | 21% | - | - | 33% | - | - |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cost Benefit Analysis for energy system | - | - | - | - | - | 41% | - | - | 29% | - |
| Label and energetic certification | - | - | - | - | 6% | - | 21% | - | - | 1% |
| Information Offices for energy efficiency solutions | - | - | - | - | - | - | 51% | - | 33% | 82% |
| Subsidy for energy production | - | - | - | - | - | 8% | 27% | 41% | 51% | 39% |

**Table 11.10 - <u>Technological Tools for energy efficiency in buildings</u>**

**<u>(Grades from 1 to 10, 1 less important – 10 really important)</u>**

| Grades | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Smart Thermostat | - | - | - | - | 58% | - | 32% | - | 69% | - |
| Led Lighting | - | - | - | - | - | - | 21% | 23% | 30% | 22% |
| Energy Management | - | - | - | - | - | 16% | 11% | 45% | 22% | - |
| Energy Start Disposal | - | - | - | - | 5% | - | - | 40% | 37% | - |
| Electric Charge Station | - | - | 9% | - | - | 24% | 17% | - | - | - |
| Smart Power Strip | - | - | - | - | 61% | 45% | 59% | 26% | - | - |

**Table 11.11 - <u>Energy efficiency policies in transportation</u>**

**<u>(Grades from 1 to 10, 1 less important – 10 really important)</u>**

| Grades | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Building regulations | - | - | - | - | - | - | - | 36% | - | 91% |
| Information on energy system | - | - | - | - | - | - | 33% | 55% | - | - |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Subsidies on energy efficiency buildings | - | - | - | - | - | 13% | - | 81% | - | - |
| Training and networking on industry construction | - | - | - | - | - | 39% | 4% | 25% | 2% | - |
| Promotion of energy services in efficient buildings | - | - | - | - | - | - | 9% | 43% | 56% | 8% |
| Research and development and use of best technologies for building construction | - | - | - | - | - | 33% | - | 75% | 60% | - |

**Table 11.12 - Energy efficiency policies in buildings**

**(Grades from 1 to 10, 1 less important – 10 really important)**

| Grades | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Smart Tire | - | - | - | - | - | - | 10% | 12% | 31% | - |
| Policy on fuel for cars | - | - | - | - | 18% | - | 70% | 63% | 80% | - |
| Policy on fuel for heavy goods vehicles | - | - | - | - | 33% | - | - | 71% | 69% | - |
| Eco – driving technologies | - | - | - | - | - | - | 49% | 56% | 82% | - |
| Best information on vehicles certifications | - | - | - | - | - | 13% | - | - | 29% | - |
| Tax subsidies for efficient energy systems | - | - | - | - | - | 57% | 23% | 11% | 36% | - |

### 11.4 International EUFORIE Workshop about Energy Efficiency

An “International Workshop on costs and benefits of energy efficiency - Scenarios in Italy and Europe” was held in Rome on November 18 at the headquarters of the GSE (Energy Services).

It was organised jointly by the University of Naples Parthenope and Federesco, to explore the theme of energy efficiency and to implement the cooperation between institutions, research community and civil society, to increase participation and collaboration on issues of great environmental and social relevance.

This initiative took place as part of SMACC (Smart City Coaching) and EUFORIE (EUropean Futures of Energy Efficiency) European projects and involved qualified operators in the energy sector, who actively participated in the roundtable discussion and filled out, in paper form during the conference and later in electronic form, a questionnaire related to energy efficiency.

Among others, participants belonging to Parthenope University of Naples, the University of Turku Finland Futures Research Centre, the Autonomous University of Barcelona, the University of Rome “La Sapienza”, the University “Ca' Foscari” of Venice, Emergency Onlus, Aura Energy Srl, VPE Srl, Easy Energy Srl, PERSUD, A&C Ecotech Srl, Telservice Srl, the Energy Commission of the Order of Engineers of Naples, the Italian Association of Consumers Energy Process (AICEP), the City of Neptune took part of the event. In total, about 150 partecipants attended the morning session, with speeches given by representatives of the Ministry of Environment, the Ministry of Economy, the Ministry of Foreign affairs, the National Energy Agency ENEA, the Energy Market Authority GSE, and a number of ESCo’s from all over Italy. The topic of the morning session was about National regulations, perspectives and futures of energy efficiency.

### 1.5 Afternoon Session “Methods of measurement and rating of energy efficiency”

In the afternoon, the session "Methods of measurement and rating of energy efficiency" took place, where stakeholders shared their experiences on the issue of energy efficiency. There was a debate about the initiatives carried out by the ESCos, associations, universities and Commissions and Orders in the sector. Everyone pointed out issues, strategies and solutions adopted in the energy sector, mainly aimed at implementing environmental and social benefits. Biomass energy production process was analysed using different methods, in order to estimate energy consumption and the environmental impact, and to provide an alternative to energy production from fossil fuels. The analyses, however, revealed that this alternative has proved to be inefficient, because the produced energy does not seem to be enough to pay back the energy investment necessary for the production process. It seems clear that it is not possible to identify in advance the most efficient solution, but we need to analyse possible alternatives before arriving at the final choice. The methods used depend on the policies and goals to be achieved, which should not only reflect economic benefits, but also respond to environmental, physical and social aspects.

For example, the discussion showed that stakeholders who benefit from the different choices are numerous and belong to different social groups; therefore, the choices made must also consider different social parameters.

In addition, since the extraction of any kind of material implies an impact and the choices presume different costs, benefits and perspectives, the methods used for these analyses are various.

One of these methodology is the Life Cycle Analysis, which aims to estimate the resulting environmental impacts (such as climate change, eutrophication, land use, human toxicity, acidification, etc.) and to produce goods from raw material mining to disposal and possible recycling of products, considering the entire production chain including associated services, such as the necessary transportation, electricity use and production phases.

Then, circular economy and planning strategies were discussed, to implement an efficient process of reuse and recycling through the experience of participants and initiatives carried out in Italy, Europe and worldwide. It emerged that interpreting society's metabolism is an essential aspect, though articulated and complex, so it first requires a rigorous analysis of the problem, a careful planning and finally a strategy, taking into account all the different aspects. An example is financial subsidies, in order to guide the choices of the stakeholders in the sector. This instrument is considered necessary, but not sufficient to strengthen a winning strategy line.

Later on, validation of energy projects was examined. As these interventions often provide a chance of failure, because of both the adopted procedures and the technical aspects to be respected, there is the possibility to entrust accredited bodies and experts in the field with these initiatives, to guarantee that local regulations are respected. Energy efficiency measures include different work activities, supplies and services; this means that the project also covers the technical and financial aspects, as well as the maintenance and management of the property. The assessment is a verification of an integrated process for corrective actions in order to increase the probability of success, which is not only a direct result of correct technical parameters, but also the result of an efficient contract.

It also emerged that there is a need to address the energy efficiency complex system in an integrated manner, for example by acting on the educational system and increasing the energy efficiency of school buildings. Therefore, it is important to focus on technologies that can solve this complex problem. A practical example discussed concerned the tax deductions, which has been active for several years now, but lacks a database to draw information from. Without such an integrated database, there is a consequent lack of information and awareness on the benefits of this financial instrument. One aspect to focus on should be the training and dissemination of information through conferences, thematic meetings and study days.

The discussion continued by addressing the energy efficiency theme, comparing the implementation of systems in Italy to other countries in Europe, like Germany, and outside Europe, such as China and the United States. It emerged that in Germany, for example, despite increasing the capacity of renewable energy plants, there was no radical reduction in pollutant emissions into the atmosphere, according to the studies. This happened because the electrical networks are still dependent on fossil fuels, thus the renewable energy plants are not autonomous, but they still depend on the production of coal, gas, etc. From the debate, it seemed that a possible solution could be linked to the consuming model, or to new energy storage technology, not only relying on the system of subsidies, as it is useful in the short term but not in the long run.

An interesting initiative shared during the day was conducted by an organization from Campania region. It concerned the decrease of energy consumption through the renovation of a house in a nineteenth century's building, in order to implement the energy efficiency by 25%. During preliminary design, they took account of the orientation and exposure of the property. Northern and western walls were insulated; the ceiling, the air chamber and the wood frames were modified, and this produced a better noise insulation. They used a system of ventilation with heat recovery, thermostatic valves, hot-water mixers, a separate electrical grid (with its own outlets) for the photovoltaic system. This, of course, increased the energy class of the building.

Finally, we got into the initiative jointly conducted by Emergency Onlus and the Ca' Foscari University of Venice, that participated in the design of a hospital in Sudan, a centre of excellence for cardiac surgery, built from scratch. The building was designed choosing advanced solutions for energy efficiency, but at the same time saving energy resources and allowing it to contain the economic spending. For example, considering the climatic context in which the building is, a major objective was to cool the air, and for this reason different technical solutions were adopted to implement energy efficiency and to limit the financial resources. The popularisation of the initiative has been very wide, in order to raise awareness and increase the number of supporters of the foundation, since it is a positive example of energy efficiency improvement action, with social implications.

# CHAPTER 12 - NATIONAL AND REGIONAL ECONOMIES.

## Social metabolism, environmental support, and resource constraints to economic growth. Case studies on Italy, Brazil, Scotland, and China.

*Introduction*

When assessing the sustainability of a regional or a national social-ecological system, there are so many different single-dimension trends of environmental, resource use, social, and economic aspects of these systems that they cannot be coherently assessed without resorting to some form of synthesis to derive one or a limited set of indicators that coherently and systematically represent sustainability outcomes.

The leading international organizations, such as the International Trade Centre (ITC), quantify traded goods in terms of their mass and the money paid for them. This is because economic assessments of trade most often only focus on the money balance. These analyses do not take into proper account the quality of the traded resources, as well as the related environmental consequences, both from the point of view of the depletion of energy and materials and of the pollution generated by extraction and preliminary processing in the exporting country (Bargigli et al., 2004; Pereira et al., 2013).

Performance indicators for industrial parks, regions and nations have been developed, based on well-known assessment methods: embodied energy, material flow analysis (MFA), life-cycle analysis (LCA), $CO_2$ emissions, and economic returns (Geng et al., 2012). These indicators individually or in combination do not necessarily provide a fully adequate characterisation since they were not designed from the outset to assess whole-systems, closed-loops, and feedback features that are key characteristics of a circular economy (Geng et al., 2013). Some disregard flow quality and characteristics and the complexity of interactions between the natural environment and socioeconomic systems (Huang et al., 2006).

To overcome the above-mentioned limitations of the unidimensional or narrowly focused analysis at the national scale, environmental scientists at Unversity of Florida examined for UNEP the material and energy bases for national economies (UNEP, 2012). They created an extensive database, the National Environmental Accounting Database (NEAD), compiling global energy, material and money flows, aggregated by national political boundaries, with systemic indicators such as the environmental load and the resource use intensity, among others. For more than 130 national systems, environmental sources, data for production, extraction, and trade flows were used to implement environmental evaluation with the Emergy Accounting Method (EMA) (Odum, 1988, 1996; Brown and Ulgiati, 2004a and 2004b). EMA incorporates the environment by accounting for the work done by nature to generate resources (natural capital) and provide ecosystem services. It expresses all resources on a common basis, in solar equivalents (abbreviated sej, for solar emjoules), which makes the work of environmental systems and human systems comparable and analytical insights more coherent. It recognizes that the human/economic system is a subsystem of the larger geobiosphere system that provides flows of energy and material resources that directly or indirectly contribute to human quality of life, but which often have no markets and cannot meaningfully be valued using willingness-to-pay (Brown and Ulgiati, 2011).

We investigated selected national economies, in order to generate our own database on countries where we have Partners that may help us to identify relevant data and interpret results properly. These countries were, of course, Italy, Scotland (where we collaborate with the James Hutton Institute, Aberdeen), Brazil (where we collaborate with UNIP-Universidade Paulista, Sao Paulo) and China, where we collaborate with a large number of Universities in Beijing, Shanghai, GuangZhou, and Macao, among others.

*Italy*

Italy is a peninsula located in southern Europe, in the middle of the Mediterranean Sea with over 300 thousand square kilometers, characterized by different climatic characteristics, complex topography and high volcanic activities. Total resident population was 60 million people in 2008, taken as the reference year for this study, and was 59.8 million in 2016, pretty stable. In the same year, the Gross Domestic Product was about 2.3 trillion of US$, but recorded a drop of 1.0 %, with a sharp reversal of the growth trend that characterized the previous two-years (+2.0 % in 2006 and +1.6 % in 2007) (ISTAT, 2009). The Italian GDP in 2008 were composed by 2.0 % from the agricultural and animal products sector, 20.8 % from the industry sector, 6.2 % from the construction sector and 71.1% from the services sector. Primary products made up for 2.2 % of all exports in 2008 (US$ 8.0 billion), including mainly minerals, animals and agricultural goods; over 95 % of the exports were composed by industrialized products (semi manufactured and manufactured). The top exported basic products were machinery and mechanical appliances (including transportation and machinery and equipment electrical) that reached 148.0 billion of US$, textiles and clothing (US$ 27.3 billion). In spite of the economic crisis and recession trends started in the year 2008 worldwide, Italy was the seventh top world exporter in the year 2008, with US$ 548 billion, and the eighth importer with US$ 568 billion (ISTAT, 2008). The main Italian commercial partners in 2008 were Europe (US$ 384.1 billion exported and US$ 366.2 billion imported), United States (56.3 billion exported and US$ 36.2 billion imported), Asia (US$ 67.9 billion exported and US$ 98.5 billion imported) and Africa (26.7 billion exported and US$ 56.9 billion imported) (ISTAT, 2008).

*Brazil*

Brazil is a continent-sized country with more than 8.5 million $km^2$ located on the east coast of South America by the Atlantic ocean. The country presents six different natural biomes and various climates, from semi-arid deserts to rainforests, with 6.7 million $km^2$ of natural forests (MMA, 2007). According to the Gross Domestic Product index (IMF, 2010), Brazil is the eighth economy in the world. However, with a population of over 190 million people in 2008, the country has a GDP per capita lower than other countries of the same region (Argentina, Chile and Uruguay), and a HDI of 0.80. The Brazilian GDP in 2008 was composed by 5.9 % fraction from the agricultural and animal products sector, by 27.9 % from the industry sector, and by 66.2 % from the service sector. The largest contributions were from commerce (12.5 % or US$ 178 billion), transport and postal services (5,0 % or US$ 72 billion), civil construction (4.9 % or US$ 70 billion), agriculture and forestry (4.0 % or US$ 58 billion), industries of food and beverage (2,2 % or US$ 32 billion), and oil and natural gas (2.1 % or US$ 31 billion) (IBGE, 2011). Brazil was the twenty-second world exporter in 2008, with US$ 198 billion, and twenty-fourth importer with US$ 183 billion (MDCI, 2010). The country is one the top producers and exporters of minerals (29 billion tons of ore reserves), making up for 15 % of the total iron ore extracted yearly in the world (372 million tons equivalent to more than US$ 16.5 billion in 2008), which also represents 8.36 % of the total exported value. Besides that, Brazil is listed among the top ten producers of gold, tin, zinc, uranium, manganese, phosphates, nickel, niobium, and bauxite (IBRAM, 2010). Primary resource were equivalent to 37 % of all exports in 2008 (US$ 73.0 billion), including mainly minerals, animals and agricultural goods; over 60 % of the exports were composed by industrialized products (semi manufactured and manufactured). The top exported basic products besides iron ore were raw oil products (US$ 13.5 billion), soybeans (US$ 10.9 billion) and poultry meat (US$ 5.8 billion). Semi manufactured commodities contributed with 13.7 % of total exports (US$ 27 billion), including products of iron and steel (US$ 4.0 billion), wood chemical pulp (US$ 3.9 billion), and sugar from sugarcane (US$ 3.6 billion). Manufactured products presented the biggest share of exports in 2008 with 47 % of the total (US$ 92.7 billion), including airplanes (US$ 5.5 billion) and passengers vehicles (US$ 4.9 billion). The main Brazilian commercial partners in 2008 were China (US$ 20.2 billion exported and US$ 15.9 billion imported), United States (15.7 billion exported and US$ 20.2 billion imported) and Argentina (US$ 12.8 billion exported and US$ 11.3 billion imported). Italy imported US$ 4.8 billion from and exported US$ 4.6 billion to Brazil in 2008 (MDIC, 2010).

*China*

China has been the highest-speed developing economy worldwide in the last 20 years. In particular, its GDP grew from 381 billion US $ in the year 1990 to 4.98 trillion $ in the year 2010 (China Statistical Yearbook, 2010[34]). Such economic growth was accompanied by a 17% population growth (from 1.14 to 1.33 billion people; China Statistical Yearbook, 2011) in the same period, while its electricity demand has been about 6 times higher (from 0.62 TWh in the year 1990 to 3.70 TWh in the year 2009; China Statistical Yearbook, 2011) in support of both welfare and industrial production increases. Environmental concerns on both source and sink sides have also been

[34]Values in Yuan RMB were adjusted to $ according to official exchange rates from The Chinese University of Hong Kong (2000), from X-Rates.com (2011), and from Trading Economics (2011). (Figure 1.a)

growing very fast, mainly related to large mining activities for coal, mineral ores and metal extraction (China Statistical Yearbook, 2011; Na et al., 2011; Dai and Chen, 2011), large water demand for industry and urbanization (Hubacek et al., 2009; Bao and Fang, 2007), increasing urban and industrial waste management problems (Wang et al., 2008), increased soil erosion from intensive land exploitation (Heerink et al., 2009; Chen, 2007), and finally increased airborne and waterborne emissions from industrial, transport and household sectors (Li and Wei, 2011, Liu et al., 2011). The combined impacts of these economic, social, and environmental trends cannot be easily assessed by means of any monodimensional measure, be it monetary growth or energy consumption, although all of these measures disclose important aspects of the complex interplay of society and nature. China's fast economic development has been deeply investigated from many different points of view (economic, demographic, social, environmental) (Wei and Hao, 2010; Gu et al., 2006), but very seldom, if ever, the implemented approaches provide a comprehensive picture of trends and interlinkages among driving factors. For this to be possible, the investigation method must be able to assess, at the same time, aspects related to resource use (availability, quality, conversion technology, efficiency), aspects related to human preferences (market values, trade, labor intensity) and finally aspects related to environmental performance (time for resource replacement by natural cycles, resources provided for free by nature as ecosystem services, renewability and nonrenewability issues).

*The Economy of China 1978-2009*

After the 1978 economic reform and opening policy, the China National Government focused on country's economic development. This determined a long period of steady development of national economy with recent annual GDP increases in the order of 10% (China Statistical Yearbook, 2010). From 1978-2009, the Gross Domestic Product changed from 3.65E+11 RMB/yr to 3.41E+13 RMB/yr, nominally 93.6 times higher, at RMB current prices, and 21.6 times higher at $ current prices (Figure 1.a), although this may not properly indicate the real increase of purchasing power and wellbeing. The exchange ratio RMB/$ increased significantly in the investigated period, from a ratio of 1.5:1 in the year 1978 to a ratio of about 8.4:1 in the year 1995, till to a lower 6.8:1 in the year 2009 (Figure 12.1.a). Of course, the changing values of the RMB/$ ratio affect both the nominal value of the GDP and the purchasing power of local and imported commodities. In the same period, population increased from 9.56E+08 units to 1.33E+09 units, a 39% increase, so that the Yuan RMB GDP per capita increased 67 times (15 times if expressed in US $) in the last 31 years (Figure 12.1.b).

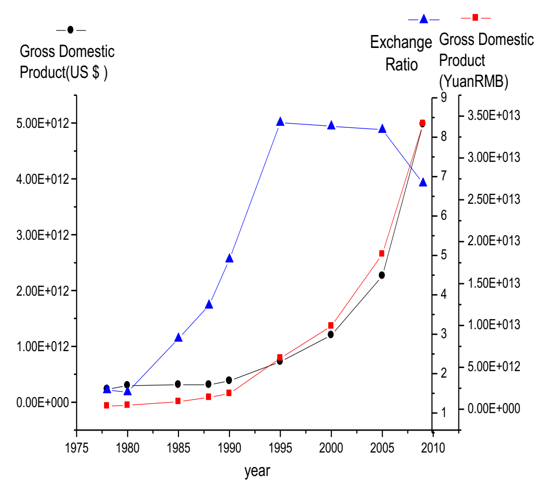



Figure 12.1.a: GDP (Yuan RMB and US $; left axis) and RMB/$ ratio (right axis)

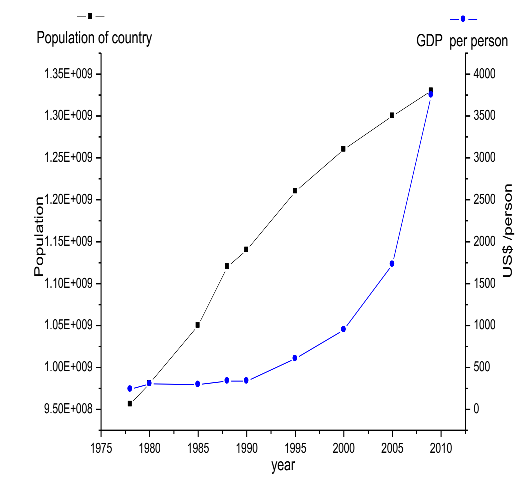



Figure 12.1.b: Population (left axis) and GDP/person (right axis)

In 1980s, Chinese economic development mainly benefited from the national reform policies. In 1990s, the property reform of China's State-Owned Enterprises (SOE’s) and the RMB exchange rate reform made the Effective Exchange Rate and the Swap Market Rate consistently lined up with the prevailing market rate. From the late 1990s, infrastructure investment and stimulated domestic demand promoted further economic development. The Government’s economic policy in recent times was to prevent economic slowdown and fight inflation. To support the planned development a large amount of domestic and foreign natural resources have been consumed. The largest resource categories driving China’s fast development can be identified as domestic coal (2.75E+9 ton, China Statistical Yearbook, 2010), metals (iron: 6.25E+08ton; aluminum: 1.29E+07 ton, among others; USGS, 2009), minerals (mainly limestone, 1.85E+08 ton, and salt, 5.85E+07 ton; USGS, 2009), and domestically produced fertilizers (phosphate, 1.80E+07 ton, and nitrogen, 4.23R+07 ton; USGS 2009). Electricity is mainly powered by domestic coal (thermal power plants, 81.81% of total 3.68E+12 kWh power generation; hydro, 15.5%, and nuclear, 1.9%), although wind and photovoltaic have been receiving more attention in the last years (China Electricity Council, 2010; Li et al, 2011). Imports of oil and natural gas are also growing as a consequence of the increasing energy demand for production and household sector (Leung, 2010). China exports a large variety of manufactured goods, agricultural products, minerals and metals, that are the basis of China’s large GDP increase. The most important production and consumption sectors are: industry (8.83E+7 workers, 1.35E+13 RMB/yr of GDP generated, and an energy consumption of about 2.09E+9 Ton of standard coal); transport (5.5E+6 workers, 1.71E+12 RMB/yr of GDP generated and an energy consumption of about 2.29E+8 ton coal); agriculture (2.97 E+8 workers, 3.52E+12 RMB/yr of GDP generated and an energy consumption of about 6.01E+7 ton coal); and households (with an energy consumption of 5.73E+7 ton coal) (China Statistical Yearbook, 2010).

*Scotland*

Scotland is not included in the NEAD system, and no other material, energy and emergy-based assessments of the country as a whole are known to be available. Given the potential diagnostic value of emergy-based characterisations, as seen from the scientific literature (Brown et al., 2009; Gasparatos and Gadda, 2009; Giannetti et al., 2013; Lou and Ulgiati, 2013; Siche et al., 2008; Yong et al., 2013), the objective of this research is to assess the feasibility of implementing such analyses for the Scotland as an example of below-national scale analysis. Therefore, EMA was applied in order to generate country-wide, consistent performance indicators.

The total land area of Scotland is about 7.8 million hectares. Located in N.W. Europe, it is exposed to prevailing westerly airflows, with a long coastline, having substantial areas with mountainous terrain and an extensive continental shelf area.

The study evaluates Scotland for two years 2001 and 2010. The main body of the results are for Scotland as a whole using the current administrative boundaries between Scotland and rest of UK. Options for assigning offshore activities and material flows are also included with the offshore (mainly oil and gas) sectors excluded, or included based on Scotland's share of the UK population or included according to the median line principle used for fisheries demarcation purposes, as suggested by Kemp and Stephen (2008). The first highlights the character of the economy without the offshore sectors, the second the *status quo* and the third a hypothetically enlarged share that could be assigned to an independent Scotland. The country was also differentiated using the degree of rurality to highlight the challenges of deriving metrics to support policy making at smaller focal scales.

Of the total area of Scotland, 94% is rural, as designated by the Scottish Governmentsince the settlements, where present, have populations of less than 3,000 persons. The classification of an area as rural is further differentiated by drive times to larger settlements with two sub-classes. Accessible rural areas are those with a less than 30 minute drive time to the nearest settlement with a population of 10,000 or more (25% of the total area of Scotland). Remote rural areas are those with a greater than 30 minute drive time to the nearest settlement with a population of 10,000 or more (69%).

The Scottish population is heavily concentrated in non-rural areas (83%, referred to in the figures and tables as the "Rest" of Scotland). From 2001 to 2010, there were no substantial changes in the balance between accessible, remote and other areas of Scotland, with an overall small movement of population from urban to accessible rural areas (1% of national population, though this represents a much larger share of the population of rural areas).

To provide a first illustration of the differences, land area, population and GDP values were disaggregated (the latter on the basis of employment and population shares). For the rural-urban comparisons in this study there were insufficient resources available to attempt to disaggregate GDP values on a more sophisticated geographical and socio-economic basis. (Table 12.1)

The study uses as much as possible the existing administrative datasets. Online data from the UK and Scottish Governments were the main sources of mass, energy and money flow data used to implement the analyses. The UK government web-site (https://www.gov.uk/government/statistics) and the International Energy Agency were the sources for data on the extraction of minerals and fossil fuels. Data about UK import/exports, in mass units, were obtained from the International Trade Centre. These were combined with data about intra-UK trade, in money terms, in order to estimate import-export values, in mass, for Scotland. UK extracted fossil fuels were assigned to Scotland using three options according to Kemp and Stephen (2008) and as used by the Scottish National Accounts Programme (SNAP).

Table 12.1. Land, Population and Gross Domestic Product share among remote and accessible rural and rest of Scotland

| | **2001** | | | **2010** | | |
|---|---|---|---|---|---|---|
| | Rest of Scotland | Accessible rural | Remote rural | Rest of Scotland | Accessible rural | Remote rural |
| **Land area** | 6% | 25% | 69% | 6% | 25% | 69% |
| **Population** | 83% | 11% | 6% | 82% | 12% | 6% |
| **GDP** | 86% | 9% | 5% | 85% | 10% | 5% |

## *Materials and Methods*

### *The investigated system*

Figure 12.2 illustrates a simplified system diagram of a national economy, drawn using Odum's energy systems symbology; a key is provided in Appendix A. The Environmental production, shown in the left part of the diagram, is directly supported by Renewable resources (R) (sun, rain, wind, geothermal). The renewable flows also provide direct and indirect (via ecosystems) support to human activities (Economic production). In addition to renewable flows, two categories of human-driven flows, local non-renewable (N) (soil, minerals, water, etc.) and imported from the beyond-Scotland economy (F) (fossil fuels, electricity, goods, machinery, labour, etc.) support the national economic system. These flows are shown as inflowing from the top of the diagram. Additional details are provided by the diagram in Figure 12.3, where the different biomas, the non-renewable sources from inside and the economic activities are shown.

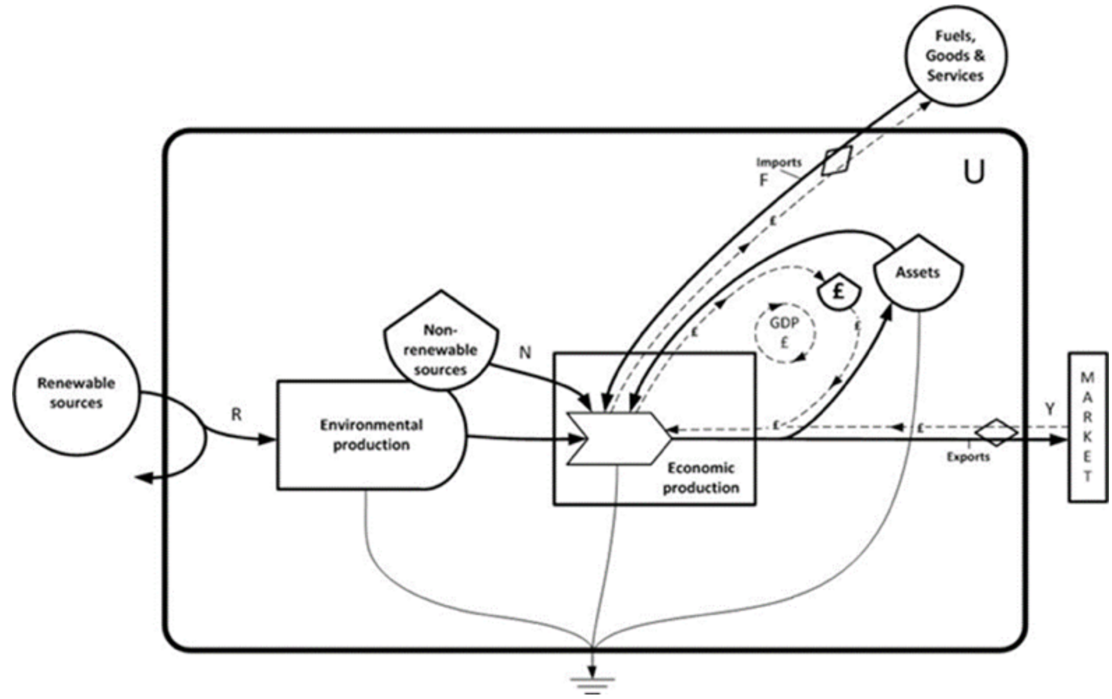



Figure 12.2. Simplified energy systems diagram for a national economy (modified from UNEP, 2012; systems symbols from Odum 1996, see Appendix)

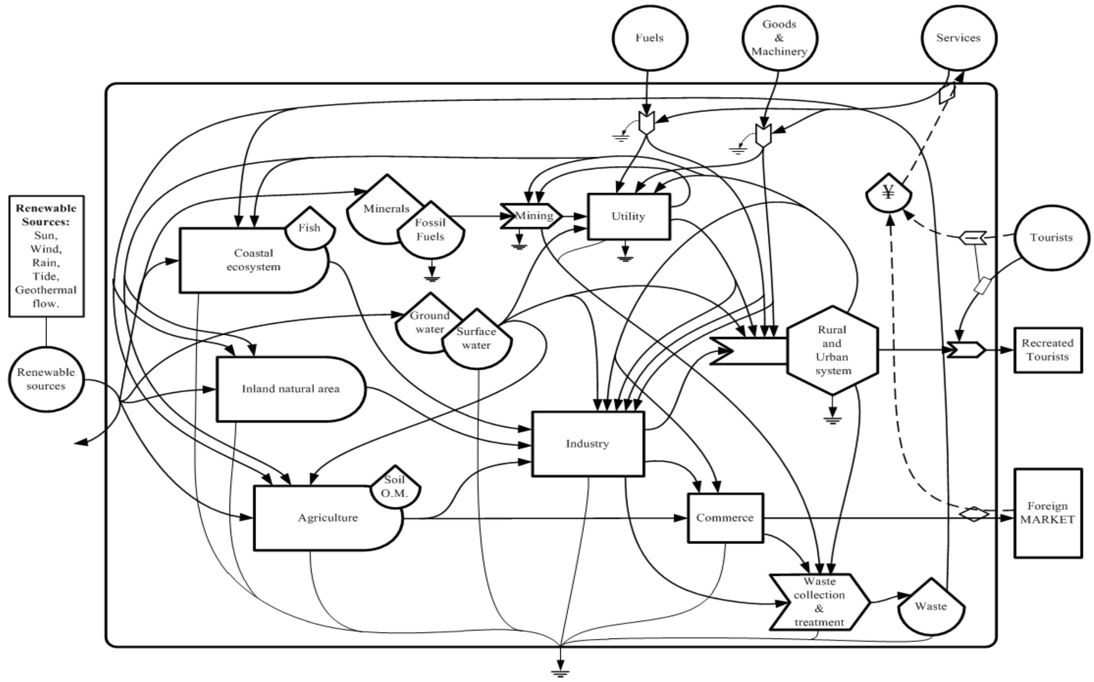



Figure 12.3 Detailed systems diagram of a national economy (systems symbols from Odum 1996, see Appendix).

After a system diagram of a country is drawn, all the mass and energy flows referred to the national economy and relevant to the emergy synthesis procedure should be identified and categorized according to the method's rules: locally available renewable and non-renewable flows, imported and exported products, imported nonrenewables and service flows associated to purchased inputs. A computational table is then created, in order to group those flows according to their characteristics and also to allow their conversion from conventional units (energy and exergy, J; mass, g; labor or services, US$, € or other currency) into emergy units (seJ). The Table represents the explicit version of the emergy equation (1):

$$Em = \sum f_i * UEV_i \qquad i = 1, \ldots, n \qquad (1)$$

where Em is the solar eMergy, $f_i$ the ith input flow of matter or energy and $UEV_i$ is the Unit Emergy Value of the i-th flow (from literature or calculated in this work).

*Methods*

Investigating only the behavior of a single process or seeking maximization of one parameter (efficiency, production cost, jobs, etc.) is unlikely to provide sufficient insight to adequately support policy-making intended to promote sustainability of a complex coupled social-ecological system. EMA, thanks to its joint focus on energy, materials, environment and economic flows, within a LCA framework, enables more holistic approaches to be taken as it expresses stocks and flows of resources, goods and services in units of the same quality, the solar energy that is used up in transformations directly and indirectly to make a product or service (solar emjoules, sej). Integration of EMA within a life cycle framework can therefore provide a biophysical perspective complementing market-based evaluation techniques. In so doing, EMA also looks at the environmental performance of a system on the global scale (that is, it considers dependencies and effects beyond the boundaries of the systems of interest).

## RESULTS

We have drawn an inventory of flows supporting the economies of the investigated countries and converted them into emergy values, according to Equation (1). Tables 12.2 to 12.9 show respectively such results (inventory and performance indicators) for Italy, Brazil, China, Scotland in selected years, depending on the availability of a full set of needed data.

Economic values are expressed as current price GDP $$ (or local currency) for Scotland and China, while instead they are expressed as PPP (Purchasing Power Parity) units for Italy and Brazil. The different choice was aimed to test how selecting different kinds of GDP measures affects the performance indicators. GDP is a measure of the total domestic economic activity. Inflation affects GDP, making it grow even in the absence of a real increase of the global national economic product. Moreover, depending on the local economy, one $ is capable to purchase different amounts of goods in different countries, which adds another uncertainty to the GDP measure, that is not captured by accounting for inflation only, i.e. by converting current prices into costant prices. According to Lomas *et al*. (2007), calculating emergy-based indicators involving GDP without considering how GDP's dynamics is affected by inflation and by local resource basis variability, would make indicators not comparable and unreliable. The only way to understand and compare GDP-composite emergy-based indicators is to keep clearly in mind the links between GDP, PPP and inflation over time. The question is if higher GDPs *per capita* indicate a real progress of buying power. For that reason, the use of PPP GDP was suggested as a more appropriate numerator for composite indicators, compared to current price and constant price GDP. We are well aware of the fact that GDP is the most commonly used indicator worldwide. However, it is easy to convert indicators calculated with reference to PPP GDP into indicators referring to conventional GDP. To help conversion and comparison, PPP GDPs for selected countries may be found at: http://www.imf.org/external/.

Table 12.2. Emergy accounting of Italy (2008)

| # | Items | Unit | Amount (unit $yr^{-1}$) | UEV (seJ $unit^{-1}$) | Ref | Emergy (seJ $yr^{-1}$) |
|---|---|---|---|---|---|---|
| Renewable local sources | | | | | | |
| 1 | Solar radiation | J | 1.67E+21 | 1 | [a] | 1.67E+21 |
| 2 | Deep heat | J | 9.04E+17 | 5.80E+04 | [b] | 5.21E+22 |
| 3 | Tide | J | 3.65E+16 | 7.40E+04 | [c] | 1.03E+21 |
| 4 | Wind | J | 5.21E+18 | 2.50E+03 | [c] | 1.31E+22 |
| 5 | Rainfall | J | 7.63E+17 | See Appendix | - | 5.08E+21 |
| 6 | Waves | J | 2.91E+18 | 5.10E+04 | [a] | 1.49E+23 |
| 7 | Marine currents | J | - | - | - | - |
| Slow-renewable local sources | | | | | | |
| 8 | Forest extraction | J | 0.00E+00 | 5.86E+04 | [a] | 0.00E+00 |
| 9 | Fishery | J | 3.78E+15 | 3.35E+06 | [a] | 1.27E+22 |
| 10 | Water | J | 0.00E+00 | 2.80E+05 | [d] | 0.00E+00 |
| 11 | Soil loss: organic matter | J | 1.20E+17 | 1.24E+05 | [e] | 1.26E+22 |
| Non-renewable local sources | | | | | | |
| 12 | Coal | J | 0.00E+00 | 6.71E+04 | [f] | 0.00E+00 |
| 13 | Natural gas | J | 3.71E+17 | 8.05E+04 | [f] | 3.25E+22 |
| 14 | Oil | J | 2.18E+17 | 9.06E+04 | [f] | 3.57E+23 |
| 15 | Minerals | g | 4.13E+14 | See Appendix | - | 6.95E+23 |
| 16 | Metals | g | 0.00E+00 | See Appendix | - | 0.00E+00 |
| Imports | | | | | | |
| 17 | Fuels | J | 7.37E+18 | See Appendix | - | 6.62E+23 |
| 18 | Metals | g | 2.74E+13 | See Appendix | - | 2.89E+23 |
| 19 | Minerals | g | 3.77E+13 | See Appendix | - | 6.84E+22 |
| 20 | Agriculture | g | 7.77E+12 | See Appendix | - | 8.62E+21 |
| 21 | Animal products | g | 2.63E+15 | See Appendix | - | 1.40E+22 |
| 22 | Fishery products | J | 9.09E+14 | 3.35E+06 | [a] | 3.05E+21 |
| 23 | Plastics | g | 1.90E+12 | 5.29E+09 | [g] | 1.37E+22 |
| 24 | Chemicals | g | 2.16E+13 | 6.38E+09 | [a] | 1.38E+22 |
| 25 | Machinery and transport | g | 9.06E+12 | 1.10E+10 | [h] | 1.02E+23 |
| 267 | Refined goods | J | 1.64E+17 | See Appendix | [g] | 3.81E+23 |
| 27 | Electricity | J | 1.55E+17 | 3.36E+05 | [c] | 3.89E+22 |
| 28 | Services for Imports (PPP units) | US$ | 5.03E+11 | 2.25E+12 | [i] | 1.13E+24 |

[a] Odum, 1996; [b] Odum, 2000; [c] Odum *et al.*, 2000; [d] Buenfil, 2001; [e] Bargigli and Ulgiati, 2003 [f] Brown and Ulgiati, 2004; [g] Buranakarn, 1998; [h] Odum et al., 1987b; [i] Sweeney et al., 2007 modified

Table 12.3. Demographic, economic and emergetic indicators, Italy 1984, 1989, 1991, 1995, 2000, 2002, and 2008.

| Indicators | Unit | 1984 | 1989 | 1991 | 1995 | 2000 | 2002 | 2008 |
|---|---|---|---|---|---|---|---|---|
| Population | mi people | 56.64 | 56.70 | 56.76 | 57.33 | 57.84 | 57.32 | 60.05 |
| PPP GDP | bi US$ | 700.78 | 946.06 | 1,051.45 | 1,204.88 | 1,438.57 | 1,451.08 | 1,814.56 |
| PPP GDP per capita | US$ $cap^{-1}$ | 12,381.75 | 16,672.39 | 18,544.09 | 21,015.47 | 24,869.81 | 25,460.34 | 30,686.97 |
| Inflation | % | 10.9 | 6.3 | 6.2 | 5.4 | 2.6 | 2.6 | 2.1 |
| R (local renewable flow) | seJ $yr^{-1}$ | 1.49E+23 | 1.49E+23 | 1.49E+23 | 1.49E+23 | 1.49E+23 | 1.49E+23 | 1.49E+23 |
| N (local nonrenewable flow) | seJ $yr^{-1}$ | 5.03E+23 | 5.98E+23 | 8.41E+23 | 8.01E+23 | 7.41E+23 | 5.77E+23 | 7.60E+23 |
| F (total imports) | seJ $yr^{-1}$ | 8.99E+23 | 1.32E+24 | 1.37E+24 | 1.69E+24 | 2.47E+24 | 2.27E+24 | 2.41E+24 |
| U (total emergy used) | seJ $yr^{-1}$ | 1.55E+24 | 2.07E+24 | 2.36E+24 | 2.64E+24 | 3.36E+24 | 3.00E+24 | 3.32E+24 |
| Total exports | seJ $yr^{-1}$ | 3.95E+23 | 5.23E+23 | 5.17E+23 | 7.64E+23 | 1.40E+24 | 1.46E+24 | 1.50E+24 |
| Emergy per capita | seJ $cap^{-1}$ | 2.74E+16 | 3.64E+16 | 4.08E+16 | 4.50E+16 | 5.82E+16 | 5.23E+16 | 5.53E+16 |
| Emergy density | seJ $m^{-2}$ | 5.15E+12 | 6.87E+12 | 7.70E+12 | 8.57E+12 | 1.12E+13 | 9.96E+12 | 1.10E+13 |
| Renewable fraction of emergy use, %REN | - | 10% | 7% | 6% | 6% | 4% | 5% | 4% |
| Imported fraction of emergy use | - | 0.58 | 0.64 | 0.59 | 0.66 | 0.74 | 0.76 | 0.73 |
| Emergy to money ratio | seJ $US\$^{-1}$ | 4.48E+12 | 3.63E+12 | 3.43E+12 | 3.10E+12 | 3.13E+12 | 2.52E+12 | 1.42E+12 |
| EYR (Y/F) | - | 1.72 | 1.57 | 1.72 | 1.56 | 1.36 | 1.32 | 1.38 |
| ELR ((N+F)/R) | - | 9.41 | 12.87 | 14.56 | 16.32 | 21.57 | 19.12 | 21.28 |
| EIR (F/(R+N)) | - | 1.38 | 1.77 | 1.38 | 1.78 | 2.78 | 3.13 | 2.65 |
| ESI (EYR/ELR) | - | 0.26 | 0.17 | 0.17 | 0.14 | 0.09 | 0.10 | 0.06 |
| Emergy exchange ratio (imp/exp) | - | 2.27 | 2.53 | 2.64 | 2.22 | 1.77 | 1.56 | 1.61 |

Table 12.4. Emergy accounting of Brazil (2008)

| # | Items | Unit | Amount (unit $yr^{-1}$) | UEV (seJ $unit^{-1}$) | Ref | Emergy (seJ $yr^{-1}$) |
|---|---|---|---|---|---|---|
| Renewable local sources | | | | | | |
| 1 | Solar radiation | J | 3.80E+22 | 1 | [a] | 3.80E+22 |
| 2 | Deep heat | J | 1.59E+19 | 5.80E+04 | [b] | 9.22E+23 |
| 3 | Tide | J | 1.10E+19 | 7.40E+04 | [c] | 8.14E+23 |
| 4 | Wind | J | 1.20E+19 | 2.50E+03 | [c] | 3.00E+22 |
| 5 | Rainfall and river | J | 8.56E+19 | See Appendix | - | 7.86E+23 |
| 6 | Waves | J | 2.42E+18 | 5.10E+04 | [a] | 1.23E+23 |
| 7 | Marine currents | J | 3.70E+16 | See Appendix | - | 6.86E+23 |
| Slow-renewable local sources | | | | | | |
| 8 | Forest extraction | J | 8.69E+18 | 5.86E+04 | [a] | 5.09E+23 |
| 9 | Fishery | G | 1.07E+12 | 2.78E+11 | [a] | 2.97E+23 |
| 10 | Ground water | J | 0.00E+00 | 2.80E+05 | [d] | 0.00E+00 |
| 11 | Soil loss: organic matter | J | 2.32E+18 | 1.24E+05 | [e] | 2.88E+23 |
| Non-renewable local sources | | | | | | |
| 12 | Coal | J | 1.04E+17 | 6.71E+04 | [f] | 7.00E+21 |
| 13 | Natural gas | J | 8.96E+17 | 8.05E+04 | [f] | 7.21E+22 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 14 | Oil | J | 3.94E+18 | 9.06E+04 | [f] | 3.57E+23 |
| 15 | Minerals | G | 3.61E+14 | See Appendix | - | 9.16E+23 |
| 16 | Metals | G | 1.02E+15 | See Appendix | - | 1.96E+23 |
| Imports | | | | | | |
| 17 | Fuels | J | 7.90E+18 | See Appendix | - | 7.12E+23 |
| 18 | Metals | G | 6.59E+11 | See Appendix | - | 5.85E+21 |
| 19 | Minerals | g | 9.40E+13 | 2.22E+09 | [g] | 2.09E+23 |
| 20 | Agriculture | g | 8.61E+12 | See Appendix | - | 2.48E+22 |
| 21 | Animal products | g | 1.75E+12 | See Appendix | - | 6.71E+22 |
| 22 | Fishery products | g | 2.10E+11 | 2.78E+11 | [a] | 5.84E+22 |
| 23 | Plastics | g | 1.01E+11 | 5.29E+09 | [g] | 5.34E+20 |
| 24 | Chemicals | g | 1.40E+13 | 6.38E+09 | [a] | 8.93E+22 |
| 25 | Machinery and transport | g | 6.52E+11 | 1.10E+10 | [h] | 7.17E+21 |
| 26 | Refined goods | g | 8.55E+11 | 2.69E+09 | [g] | 2.30E+21 |
| 27 | Electricity | J | 1.51E+17 | 3.36E+05 | [c] | 5.06E+22 |
| 28 | Services for Imports (PPP units) | US$ | 1.73E+11 | 2.25E+12 | [i] | 3.89E+23 |

[a] Odum, 1996; [b] Odum, 2000; [c] Odum et al., 2000; [d] Buenfil, 2001; [e] Bargigli and Ulgiati, 2003 [f] Brown and Ulgiati, 2004; [g] Buranakarn, 1998; [h] Odum et al., 1987b; [i] Sweeney et al., 2007 modified

Table 12.5 Demographic, economic and emergetic indicators for Brazil in 1981, 1989, 1996, 2000, and 2008

| Indicator | Unit | 1981 | 1989 | 1996 | 2000 | 2008 |
|---|---|---|---|---|---|---|
| Population [A] | mi people | 121.38 | 144.00 | 161.32 | 169.80 | 189.61 |
| PPP GDP [B] | bi US$ | 467.54 | 790.84 | 1,081.17 | 1,256.52 | 1,978.14 |
| PPP GDP per capita | US$ $cap^{-1}$ | 3,760.20 | 5,446.34 | 6,701.91 | 7,400.00 | 9,355.98 |
| Inflation [B] | % | 101.7 | 1,430.7 | 16.0 | 6.0 | 4.4 |
| | | | | | | |
| R (local renewable flow) | seJ $yr^{-1}$ | 7.86E+23 | 7.86E+23 | 7.86E+23 | 7.86E+23 | 7.86E+23 |
| N (local nonrenewable flow) | seJ $yr^{-1}$ | 4.71E+23 | 1.22E+24 | 1.23E+24 | 1.48E+24 | 2.69E+24 |
| F (total imports) | seJ $yr^{-1}$ | 2.82E+23 | 2.64E+23 | 5.01E+23 | 5.97E+23 | 1.62E+24 |
| Imported services | seJ $yr^{-1}$ | 1.05E+22 | 1.27E+22 | 1.20E+23 | 1.58E+23 | 3.89E+23 |
| U (total emergy used) | seJ $yr^{-1}$ | 1.54E+24 | 2.27E+24 | 2.52E+24 | 2.86E+24 | 5.09E+24 |
| Total exports | seJ $yr^{-1}$ | 1.92E+23 | 5.55E+23 | 7.48E+23 | 1.77E+24 | 1.74E+24 |
| Exported services | seJ $yr^{-1}$ | 1.92E+22 | 2.50E+22 | 1.06E+23 | 1.20E+23 | 4.59E+23 |
| Emergy per capita | seJ $yr^{-1}$ | 1.26E+16 | 1.57E+16 | 1.49E+16 | 1.60E+16 | 2.48E+16 |
| Emergy density | seJ $m^{-2}$ | 1.79E+11 | 2.65E+11 | 2.81E+11 | 3.20E+11 | 5.51E+11 |
| Renewable fraction of emergy use, %REN | - | 51% | 35% | 33% | 29% | 17% |
| Imported fraction of emergy use | - | 0.18 | 0.12 | 0.20 | 0.21 | 0.32 |
| Emergy to money ratio | seJ $US\$^{-1}$ | 3.29E+12 | 2.88E+12 | 2.33E+12 | 2.29E+12 | 2.57E+12 |
| EYR (U/F) | - | 5.46 | 8.62 | 5.04 | 4.80 | 3.15 |
| ELR ((N+F)/R) | - | 0.96 | 1.89 | 2.21 | 2.64 | 5.48 |
| EIR (F/(R+N)) | - | 0.22 | 0.13 | 0.25 | 0.26 | 0.46 |
| ESI (EYR/ELR) | - | 5.69 | 4.55 | 2.28 | 1.82 | 0.58 |
| Emergy exchange ratio (imp/exp) | - | 1.47 | 0.48 | 0.67 | 0.34 | 0.91 |

[A] Brazilian Institute of Geography and Statistics (IBGE, 2008)

[B] International Monetary Fund (IMF, 2008)

**Table 12.6 Emergy Evaluation of China (2009).**

| Note | Item | Raw Amount | Unit/yr | UEV (seJ/unit) (*) | Solar Emergy ($10^{20}$seJ/yr) | Emergy-based currency equivalent ($10^9$ Yuan RMB/yr) |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| RENEWABLE RESOURCES: | | | | | | |
| 1 | Sunlight | 3.47E+22 | J | 1 | 3.47E+02 | 4.03E+01 |
| 2 | Rain, chemical | 2.17E+19 | J | 3.05E+04 | 6.61E+03 | 7.68E+02 |
| 3 | Rain, geopotential | 4.20E+19 | J | 4.70E+04 | 1.98E+04 | 2.29E+03 |
| 4 | Wind, kinetic energy | 7.72E+19 | J | 2.45E+03 | 1.89E+03 | 2.20E+02 |
| 5 | Waves | 1.77E+18 | J | 5.10E+04 | 9.05E+02 | 1.05E+02 |
| 6 | Tide | 9.94E+16 | J | 7.39E+04 | 7.34E+01 | 8.53E+00 |
| 7 | Surface heat flow | 1.91E+19 | J | 5.80E+04 | 1.11E+04 | 1.28E+03 |
| NONRENEWABLE SOURCES FROM WITHIN THE SYSTEM: | | | | | | |
| 8 | Fishery extraction | 2.00E+11 | g | 1.45E+11 | 2.91E+02 | 3.38E+01 |
| 9 | Organic matter in soil eroded | 3.05E+18 | J | 7.40E+04 | 2.26E+03 | 2.62E+02 |
| 10 | Natural Gas | 3.12E+18 | J | 8.06E+04 | 2.51E+03 | 2.92E+02 |
| 11 | Oil | 8.36E+18 | J | 9.07E+04 | 7.58E+03 | 8.80E+02 |
| 12 | Coal | 8.58E+19 | J | 6.72E+04 | 5.77E+04 | 6.70E+03 |
| 13 | Minerals (mixed, §) | 3.55E+14 | g | 3.18E+09 | 1.13E+04 | 1.31E+03 |
| 14 | Metals (mixed, §) | 6.34E+14 | g | 1.96E+10 | 1.25E+05 | 1.45E+04 |
| IMPORTS AND OUTSIDE SOURCES: | | | | | | |
| 15 | Natural gas | 2.80E+17 | J | 8.06E+04 | 2.26E+02 | 2.62E+01 |
| 16 | Oil derived fuels | 1.32E+19 | J | 1.11E+05 | 1.46E+04 | 1.69E+03 |
| 17 | Coal | 1.17E+18 | J | 6.72E+04 | 7.85E+02 | 9.12E+01 |
| 18 | Metals (mixed, §) | 3.74E+13 | g | 2.46E+10 | 9.20E+03 | 1.07E+03 |
| 19 | Minerals (mixed, §) | 5.36E+13 | g | 3.29E+09 | 1.76E+03 | 2.04E+02 |
| 20 | Food & agro-products (mixed, §) | 5.43E+13 | g | 1.13E+10 | 6.11E+03 | 7.09E+02 |
| 21 | Chemicals (mixed, §) | 1.00E+14 | g | 5.90E+09 | 5.92E+03 | 6.87E+02 |
| 22 | Mach.& transport equipment | 8.83E+12 | g | 2.22E+10 | 1.96E+03 | 2.28E+02 |
| 23 | Services associated to imports | 1.01E+12 | $ | 2.00E+12 | 2.01E+04 | 2.34E+03 |
| EXPORTS: | | | | | | |
| 24 | Food & agro-products (mixed, §) | 7.38E+14 | g | 4.09E+08 | 3.02E+03 | 3.50E+02 |
| 25 | Refined fuels | 6.06E+13 | g | 1.78E+09 | 1.08E+03 | 1.25E+02 |
| 26 | Metals (mixed, §) | 9.92E+13 | g | 1.56E+10 | 1.55E+04 | 1.80E+03 |
| 27 | Minerals (mixed, §) | 3.03E+13 | g | 4.36E+09 | 1.32E+03 | 1.53E+02 |
| 28 | Chemicals (mixed, §) | 2.21E+13 | g | 1.01E+10 | 2.22E+03 | 2.58E+02 |
| 29 | Mach. & transport equipment | 5.70E+13 | g | 2.08E+10 | 1.18E+04 | 1.37E+03 |
| 30 | Services associated to exports | 1.20E+12 | $ | 5.88E+12 | 7.07E+04 | 8.21E+03 |

* UEVs based on total renewable biosphere emergy flow of 15.83E24 seJ/yr [Odum, 2000]

(§) See Appendix

**Table 12.7. Trend of selected emergy-based performance indices of China, 1978-2009.**

| Item | Name of Index | 1978 (*) | 1980 (*) | 1985 (*) | 1988 (§) | 1990 (*) | 1995 (*) | 2000 (#) | 2005 (*) | 2009 (°) | Unit |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Area of country | 9.63E+12 | 9.63E+12 | 9.63E+12 | 9.63E+12 | 9.63E+12 | 9.63E+12 | 9.63E+12 | 9.63E+12 | 9.63E+12 | $m^2$ |
| 2 | Population of country | 9.56E+08 | 9.81E+08 | 1.05E+09 | 1.12E+09 | 1.14E+09 | 1.21E+09 | 1.26E+09 | 1.30E+09 | 1.33E+09 | # |
| 3a | Gross Domestic Product | 2.31E+11 | 2.97E+11 | 3.12E+11 | 3.76E+11 | 3.81E+11 | 7.26E+11 | 1.20E+12 | 2.26E+12 | 4.98E+12 | US $/yr |
| 3b | Exchange Ratio | 1.58 | 1.53 | 2.89 | 3.73 | 4.90 | 8.37 | 8.28 | 8.19 | 6.83 | = |
| 3c | Gross Domestic Product | 3.65E+11 | 4.55E+11 | 9.02E+11 | 1.40E+12 | 1.87E+12 | 6.08E+12 | 9.92E+12 | 1.85E+13 | 3.41E+13 | Yuan RMB/yr |
| 3d | GDP per person | 2.41E+02 | 3.03E+02 | 2.97E+02 | 3.36E+02 | 3.36E+02 | 6.03E+02 | 9.49E+02 | 1.73E+03 | 3.75E+03 | US $/person |
| 4 | Renewable sources | 2.54E+24 | 2.72E+24 | 2.79E+24 | 2.10E+24 | 2.91E+24 | 2.72E+24 | 2.40E+24 | 2.79E+24 | 2.64E+24 | seJ/yr |
| 5 | Indigenous nonrenewable reserves | 3.00E+24 | 3.01E+24 | 4.01E+24 | 3.79E+24 | 4.82E+24 | 6.30E+24 | 6.53E+24 | 1.02E+25 | 2.09E+25 | seJ/yr |
| *5a* | *Dispersed Sources* | 8.37E+22 | 1.06E+23 | 1.60E+23 | 4.43E+22 | 2.03E+23 | 2.25E+23 | 2.04E+23 | 2.23E+23 | 2.55E+23 | seJ/yr |
| *5b* | *Concentrated Use* | 2.60E+24 | 2.67E+24 | 3.48E+24 | 3.69E+24 | 4.28E+24 | 5.46E+24 | 6.10E+24 | 8.74E+24 | 2.04E+25 | seJ/yr |
| *5c* | *Exported without Use* | 3.16E+23 | 2.32E+23 | 3.71E+23 | 5.21E+22 | 3.36E+23 | 6.18E+23 | 2.21E+23 | 1.22E+24 | 2.40E+23 | seJ/yr |
| 6 | Total imported emergy | 3.00E+23 | 3.42E+23 | 7.44E+23 | 6.34E+23 | 4.56E+23 | 9.62E+23 | 3.11E+24 | 7.95E+24 | 6.07E+24 | seJ/yr |
| *6a* | *Imported Fuels and Minerals* | 1.37E+23 | 1.81E+23 | 4.40E+23 | 1.46E+23 | 8.14E+22 | 2.69E+23 | 1.55E+24 | 4.67E+24 | 2.66E+24 | seJ/yr |
| *6b* | *Imported Goods* | 1.09E+23 | 1.06E+23 | 1.90E+23 | 3.41E+23 | 2.37E+23 | 3.63E+23 | 1.04E+24 | 1.90E+24 | 1.40E+24 | seJ/yr |
| *6c* | *Dollars Paid for Imports* | 1.87E+10 | 2.00E+10 | 4.23E+10 | 5.53E+10 | 5.34E+10 | 1.32E+11 | 2.25E+11 | 6.60E+11 | 1.01E+12 | $/yr |
| *6d* | *Services for Imports* | 5.43E+22 | 5.51E+22 | 1.14E+23 | 1.46E+23 | 1.38E+23 | 3.30E+23 | 5.18E+23 | 1.39E+24 | 2.01E+24 | seJ/yr |
| 7 | Total emergy inflows | 5.84E+24 | 6.07E+24 | 7.54E+24 | 6.03E+24 | 8.19E+24 | 9.99E+24 | 1.20E+25 | 2.09E+25 | 2.96E+25 | seJ/yr |
| 8 | Total emergy used, U | 5.52E+24 | 5.84E+24 | 7.17E+24 | 6.47E+24 | 7.86E+24 | 9.37E+24 | 1.18E+25 | 1.97E+25 | 2.93E+25 | seJ/yr |
| 9 | Total exported emergy | 1.02E+24 | 1.04E+24 | 1.95E+24 | 1.13E+24 | 1.69E+24 | 2.88E+24 | 6.10E+24 | 1.57E+25 | 1.06E+25 | seJ/yr |
| *9a* | *Exported Fuels and Minerals* | 3.12E+23 | 2.30E+23 | 3.66E+23 | 2.65E+23 | 2.25E+23 | 5.50E+23 | 1.23E+24 | 1.23E+24 | 1.79E+24 | seJ/yr |
| *9b* | *Exported goods* | 3.07E+23 | 4.54E+23 | 9.58E+23 | 5.05E+22 | 1.50E+23 | 2.33E+23 | 2.41E+24 | 7.85E+24 | 1.71E+24 | seJ/yr |
| *9c* | *Dollars Received for Exports* | 1.68E+10 | 1.81E+10 | 2.74E+10 | 4.75E+10 | 6.21E+10 | 1.49E+11 | 2.49E+11 | 7.62E+11 | 1.20E+12 | $/yr |
| *9d* | *Services for Exports* | 4.02E+23 | 3.56E+23 | 6.29E+23 | 8.17E+23 | 1.32E+24 | 2.10E+24 | 2.46E+24 | 6.65E+24 | 7.07E+24 | seJ/yr |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | Economic terms of trade | 0.89 | 0.91 | 0.65 | 0.86 | 1.16 | 1.13 | 1.11 | 1.15 | 1.20 | = |
| 11a | Net Trade (Exports imports) | 7.22E+23 | 6.98E+23 | 1.21E+24 | 4.99E+23 | 1.24E+24 | 1.92E+24 | 2.99E+24 | 7.77E+24 | 4.50E+24 | seJ/yr |
| 11b | Emergy Exchange Ratio (exp/imp) | 3.41 | 3.04 | 2.62 | 1.79 | 3.71 | 2.99 | 1.96 | 1.98 | 1.74 | = |
| 12 | Fraction of use that is locally renewable | 0.46 | 0.47 | 0.39 | 0.32 | 0.37 | 0.29 | 0.20 | 0.14 | 0.09 | = |
| 13 | Fraction of use that is purchased | 0.05 | 0.06 | 0.10 | 0.10 | 0.06 | 0.10 | 0.26 | 0.40 | 0.21 | = |
| 14 | Emergy use per unit area, Emergy Density | 5.74E+11 | 6.07E+11 | 7.45E+11 | 6.72E+11 | 8.16E+11 | 9.73E+11 | 1.23E+12 | 2.05E+12 | 3.05E+12 | seJ/m$^2$ |
| 15 | Emergy Use per person | 5.78E+15 | 5.95E+15 | 6.82E+15 | 5.78E+15 | 6.92E+15 | 7.78E+15 | 9.35E+15 | 1.51E+16 | 2.21E+16 | seJ/person |
| 16 | Renewable carrying capacity, at present living standard | 4.39E+08 | 4.57E+08 | 4.09E+08 | 3.63E+08 | 4.21E+08 | 3.50E+08 | 2.57E+08 | 1.85E+08 | 1.20E+08 | number of people |
| 17 | Nonrenewable carrying capacity, at same living standard | 5.17E+08 | 5.24E+08 | 6.42E+08 | 7.57E+08 | 7.14E+08 | 8.55E+08 | 1.01E+09 | 1.12E+09 | 1.21E+09 | number of people |
| 18 | Ratio of world emergy use to GWP | 2.90E+12 | 2.75E+12 | 2.70E+12 | 2.65E+12 | 2.58E+12 | 2.50E+12 | 2.30E+12 | 2.10E+12 | 2.00E+12 | seJ/$ |
| 19a | Ratio of China emergy use to GDP | 1.52E+13 | 1.28E+13 | 7.95E+12 | 4.61E+12 | 4.21E+12 | 1.54E+12 | 1.19E+12 | 1.07E+12 | 8.61E+11 | seJ/Yuan RMB |
| 19b | Ratio of China emergy use to GDP | 2.39E+13 | 1.97E+13 | 2.30E+13 | 1.72E+13 | 2.06E+13 | 1.29E+13 | 9.86E+12 | 8.73E+12 | 5.88E+12 | seJ/$ |
| 20 | Purchasing Power Ratio, PPR | 8.26 | 7.15 | 8.51 | 6.49 | 7.99 | 5.16 | 4.29 | 4.16 | 2.94 | |
| 21 | Ratio of emergy use in electricity form | 0.06 | 0.06 | 0.07 | 0.10 | 0.09 | 0.12 | 0.14 | 0.15 | 0.15 | = |
| 22a | Ratio of emergy use in fuels form | 0.35 | 0.35 | 0.35 | 0.42 | 0.41 | 0.46 | 0.25 | 0.36 | 0.28 | = |
| 22b | Total fuel use | 1.94E+24 | 2.03E+24 | 2.54E+24 | 2.70E+24 | 3.22E+24 | 4.27E+24 | 2.92E+24 | 7.14E+24 | 8.34E+24 | seJ/yr |
| 22c | Fuel use per person | 2.03E+15 | 2.07E+15 | 2.42E+15 | 2.41E+15 | 2.84E+15 | 3.54E+15 | 2.31E+15 | 5.48E+15 | 6.27E+15 | seJ/person |
| 23 | EYR | 18.43 | 17.06 | 9.64 | 10.21 | 17.23 | 9.74 | 3.80 | 2.48 | 4.83 | = |
| 24 | ELR | 1.30 | 1.23 | 1.70 | 2.11 | 1.81 | 2.67 | 4.01 | 6.50 | 10.21 | = |
| 25 | ESI | 14.15 | 13.86 | 5.65 | 4.84 | 9.51 | 3.65 | 0.95 | 0.38 | 0.47 | = |

(*) Yang et al., 2010 (#) NEAD, 2011. (§) Lan and Odum, 1994 (°) This study

Table 12.8 Emergy flows supporting Scotland in the years 2001 and 2010

| | | Solar Emergy (sej/yr) | | Onshore | | Including a population share of extra-regio | | Including a geographical share of extra-regio | |
|---|---|---|---|---|---|---|---|---|---|
| # | Item | 2001 | 2010 | *2001* | *2010* | *2001* | *2010* | *2001* | *2010* |
| **RENEWABLE SOURCES R *onshore*** | | | | | | | | | |
| 1 | Solar Radiation | 1.54E+21 | 1.51E+21 | 0.68% | 0.60% | 0.54% | 0.54% | 0.23% | 0.31% |
| 2 | Geothermal flow | 1.92E+21 | 1.92E+21 | 0.85% | 0.77% | 0.67% | 0.69% | 0.28% | 0.40% |
| 3 | Wind on land, kinetic energy | 9.54E+21 | 9.54E+21 | 4.23% | 3.83% | 3.33% | 3.41% | 1.41% | 1.97% |
| 4 | Rain, chemical potential | 1.40E+21 | 1.69E+21 | 0.62% | 0.68% | 0.49% | 0.61% | 0.21% | 0.35% |
| 5 | Rain, geopotential potential | 2.09E+21 | 2.52E+21 | 0.93% | 1.01% | 0.73% | 0.90% | 0.31% | 0.52% |
| 6 | Wave energy | 4.27E+22 | 4.27E+22 | 18.94 % | 17.13 % | 14.89 % | 15.28 % | 6.31% | 8.81% |
| 7 | Tidal energy | 4.29E+22 | 4.29E+22 | 19.02 % | 17.20 % | 14.95 % | 15.35 % | 6.33% | 8.84% |
| **LOCAL NONRENEWABLE SOURCES N** | | | | | | | | | |
| 8 | Organic matter in soil eroded | 2.02E+21 | 2.13E+21 | 0.89% | 0.86% | 0.70% | 0.76% | 0.30% | 0.44% |
| 9 | Ground water extraction | - | - | - | - | - | - | - | - |
| 9a | Drinking water | 2.38E+20 | 2.06E+20 | 0.11% | 0.08% | 0.08% | 0.07% | 0.04% | 0.04% |
| 10 | Forest Extraction | - | - | - | - | - | - | - | - |
| 11 | Fishery extraction | - | - | - | - | - | - | - | - |
| 12a | Oil (per capita share) | 1.60E+22 | 9.82E+21 | - | - | 5.60% | 3.51% | - | - |
| 12b | Oil (geographical share) | 1.76E+23 | 1.12E+23 | - | - | - | - | 26.02 % | 23.19% |
| 13a | Natural gas (per capita share) | 4.54E+22 | 2.03E+22 | - | - | 15.82 % | 7.26% | - | - |
| 13b | Natural gas (geographical share) | 2.75E+23 | 1.23E+23 | - | - | - | - | 40.69 % | 25.41% |
| 14 | Coal | 4.00E+22 | 3.34E+22 | 17.75 % | 13.39 % | 13.95 % | 11.95 % | 5.91% | 6.88% |
| 15 | Sand and Gravel | 1.65E+22 | 1.13E+22 | 7.33% | 4.54% | 5.76% | 4.05% | 2.44% | 2.33% |
| 16 | Sandstone | 1.49E+21 | 2.77E+21 | 0.66% | 1.11% | 0.52% | 0.99% | 0.22% | 0.57% |
| 17 | Igneous rock | 2.87E+22 | 3.02E+22 | 12.75 % | 12.13 % | 10.02 % | 10.82 % | 4.24% | 6.24% |
| 18 | Limestone | 2.31E+21 | 1.65E+21 | 1.02% | 0.66% | 0.80% | 0.59% | 0.34% | 0.34% |
| 19 | Peat | 4.37E+20 | 6.74E+20 | 0.19% | 0.27% | 0.15% | 0.24% | 0.06% | 0.14% |
| 20 | Clay and Shale | 1.29E+21 | 5.22E+19 | 0.57% | 0.02% | 0.45% | 0.02% | 0.19% | 0.01% |
| 21 | Fireclay | 6.14E+19 | 4.61E+18 | 0.03% | 0.002 % | 0.02% | 0.002 % | 0.009 % | 0.0010 % |
| **IMPORTED SOURCES F** | | | | | | | | | |
| 22 | Food and Live animals | 1.20E+21 | 3.86E+21 | 0.53% | 1.55% | 0.42% | 1.38% | 0.18% | 0.80% |
| 23 | Beverages and Tobacco | 3.06E+21 | 3.61E+21 | 1.36% | 1.45% | 1.07% | 1.29% | 0.45% | 0.75% |
| 24 | Crude materials, inedible, except fuels | 1.21E+22 | 6.04E+21 | 5.38% | 2.42% | 4.23% | 2.16% | 1.79% | 1.25% |
| 25 | Minerals fuels, lubricants and related materials | 5.57E+21 | 4.22E+22 | 2.47% | 16.92 % | 1.94% | 15.09 % | 0.82% | 8.70% |
| 26 | Animal and vegetable oils, fats and waxes | 2.97E+19 | 4.42E+19 | 0.01% | 0.02% | 0.01% | 0.02% | 0.00% | 0.01% |
| 27 | Chemicals and related products, nes | 1.64E+21 | 1.55E+21 | 0.73% | 0.62% | 0.57% | 0.56% | 0.24% | 0.32% |
| 28 | Manufactured goods | 4.21E+21 | 3.49E+21 | 1.87% | 1.40% | 1.47% | 1.25% | 0.62% | 0.72% |
| 29 | Machinery and transport equipment | 7.07E+21 | 3.02E+21 | 3.14% | 1.21% | 2.46% | 1.08% | 1.04% | 0.62% |
| 30 | Miscellaneous manufactured articles | 4.13E+21 | 3.63E+21 | 1.83% | 1.46% | 1.44% | 1.30% | 0.61% | 0.75% |
| 31 | Commodities/transactions not class'd elsewhere in sitc | - | - | - | - | - | - | - | - |
| 32 | Services associated to imports | 5.03E+22 | 4.70E+22 | 22.34 % | 18.85 % | 17.56 % | 16.82 % | 7.44% | 9.69% |
| | | | | 100% | 100% | 100% | 100% | 100% | 100% |
| **TOTAL EMERGY** | | | | | | | | | |
| | *Onshore* | **2.25E+23** | **2.49E+23** | | | | | | |
| | *Including a population share of extra-regio* | **2.87E+23** | **2.79E+23** | | | | | | |
| | *Including a geographical share of extra-region* | **6.77E+23** | **4.85E+23** | | | | | | |

Table 12.9 Main emergy indicators for Scotland in 2001 and 2010 calculated both including and excluding services

| ***EMERGY INDICATORS*** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Indicator** | **2001** | | | **2010** | | | **unit** |
| | *Onshore* | *Including a population share of extra-regio* | *Including a geographical share of extra-regio* | *Onshore* | *Including a population share of extra-regio* | *Including a geographical share of extra-regio* | |
| ***LOCAL SOURCES:*** | | | | | | | |
| Renewable sources (R) | 5.24E+22 | - | - | 5.24E+22 | - | - | sej/yr |
| Nonrenewable sources (N) | 9.29E+22 | 1.54E+23 | 5.44E+23 | 8.22E+22 | 1.12E+23 | 3.18E+23 | sej/yr |
| ***WITH SERVICES:*** | | | | | | | |
| Total emergy (U) | 2.35E+23 | 2.96E+23 | 6.86E+23 | 2.49E+23 | 2.79E+23 | 4.85E+23 | sej/yr |
| Imported emergy (F) | 8.94E+22 | - | - | 1.14E+23 | - | - | sej/yr |
| Exported emergy (Y) | 1.18E+23 | 2.02E+23 | 8.79E+23 | 1.12E+23 | 1.65E+23 | 5.05E+23 | sej/yr |
| Import/Export Ratio (emergy basis) | 0.76 | 0.44 | 0.10 | 1.02 | 0.69 | 0.23 | - |
| Renewable Ratio (R/U) | 0.22 | 0.18 | 0.08 | 0.21 | 0.19 | 0.11 | - |
| Environmental Loading Ratio, ELR ((N+F)/R) | 3.48 | 4.65 | 12.09 | 3.75 | 4.33 | 8.25 | - |
| Emergy Yield Ratio, EYR, (U/F) | 2.63 | 3.31 | 7.68 | 2.18 | 2.44 | 4.24 | - |
| Emergy Investment Ratio, EIR (F/(R+N)) | 0.62 | 0.43 | 0.15 | 0.85 | 0.69 | 0.31 | - |
| Emergy Sustainability Index, ESI= EYR/ELR | 0.76 | 0.71 | 0.63 | 0.58 | 0.56 | 0.51 | - |
| Emergy density (U/Area) | 3.01E+12 | 3.80E+12 | 8.80E+12 | 3.19E+12 | 3.58E+12 | 6.22E+12 | sej/m$^2$ |
| Emergy per person (U/capita) | 4.64E+16 | 5.85E+16 | 1.36E+17 | 4.77E+16 | 5.34E+16 | 9.28E+16 | sej/capita |
| Emergy intensity of currency U/GDP | 2.90E+12 | 3.59E+12 | 7.19E+12 | 2.65E+12 | 2.91E+12 | 4.37E+12 | sej/£ |
| ***WITHOUT SERVICES:*** | | | | | | | |
| Total emergy (U) | 1.85E+23 | 2.46E+23 | 6.36E+23 | 2.02E+23 | 2.32E+23 | 4.38E+23 | sej/yr |
| Imported emergy (F) | 3.90E+22 | - | - | 6.74E+22 | - | - | sej/yr |
| Exported emergy (Y) | 6.97E+22 | 1.27E+23 | 7.73E+23 | 6.74E+22 | 9.87E+22 | 4.00E+23 | sej/yr |
| Import/Export Ratio (emergy basis) | 0.56 | 0.31 | 0.05 | 1.00 | 0.68 | 0.17 | - |
| Renewable Ratio (R/U) | 0.28 | 0.21 | 0.08 | 0.26 | 0.23 | 0.12 | - |
| Environmental Loading Ratio, ELR ((N+F)/R) | 2.52 | 3.69 | 11.13 | 2.85 | 3.43 | 7.35 | - |
| Emergy Yield Ratio, EYR, (U/F) | 4.73 | 6.30 | 16.30 | 3.00 | 3.45 | 6.49 | - |
| Emergy Investment Ratio, EIR (F/(R+N)) | 0.27 | 0.19 | 0.07 | 0.50 | 0.41 | 0.18 | - |
| Emergy Sustainability Index, ESI= EYR/ELR | 1.88 | 1.71 | 1.46 | 1.05 | 1.01 | 0.88 | - |
| Emergy density (U/Area) | 2.37E+12 | 3.15E+12 | 8.16E+12 | 2.59E+12 | 2.98E+12 | 5.62E+12 | sej/m$^2$ |
| Emergy per person (U/capita) | 3.65E+16 | 4.86E+16 | 1.26E+17 | 3.87E+16 | 4.45E+16 | 8.38E+16 | sej/capita |
| Emergy intensity of currency U/GDP | 2.28E+12 | 2.98E+12 | 6.67E+12 | 2.15E+12 | 2.42E+12 | 3.95E+12 | sej/£ |

## *Discussion*

### *Italy and Brazil*

Tables 12.2 to 12.5 show the inventory of resource flows supporting the economies of Italy and Brazil as well as their demographic, economic, emergetic indicators in selected years. The total emergy use (U) and the emergy use per person suggest a measure of potential standard of life (intended as availability of resources and goods). Of course, total and average per capita values hide the hierarchy of unequal access to resources by different social classes, for which a more detailed assessment across space, age and income classes would be needed; yet, these values provide a starting point to understand the time evolution of a country as a whole as well as to compare countries from the point of view of their welfare development potential. Table 12.5 shows that the use of resources in Brazil increased in the investigated period (with total emergy and per capita emergy use increased respectively by 112 % and 231 % from 1981 to 2008) emphasizing the ongoing development of this country via the increased availability of supporting resources. Approximately in the same period, the total emergy use and the emergy per person of Italy respectively increased by more than 102% and 114 % (Table 12.3). Such increase, considering that Italy does not have energy sources and stocks of minerals, suggests a still huge ability of the Italian economic system to attract and acquire primary resources from abroad to support its welfare, although this trend seems to be slowing down in the most recent years.

The empower density, a measure of spatial concentration of emergy flow within a system, shows a higher value for Italy around 1.10E+13 seJ $m^{-2}$ in the year 2008, while it was only 5.51E+11 seJ $m^{-2}$ in Brazil in the same year. This suggests a spatial hierarchy, with industrialized countries in the top positions, followed by nations characterized by less concentrated or rural economies. The Brazilian Emergy Yield Ratio (EYR) declined from 5.46 in the year 1981 to 3.15 in the year 2008, indicating that the Brazilian economy is slowly shifting from a strong reliance on local resources to increased use of imported goods. Also the EYR of the Italian economy slowly decreased from 1.72 (in the year 1984) to 1.38 (in the year 2008) underlining its increasing dependence from imports, mainly fossil energy resources. Values of EYR lower than 2 are alarming, because they indicate that the national economy is no longer based on the exploitation of local resources, but instead it only converts primary resources imported from outside. As a consequence of the fact that emergy imports and local emergy extraction in Italy are mainly nonrenewable, the Environmental Loading Ratio (ELR) of Italy increased from 9.41 in the year 1984 to 21.28 in the year 2008, indicating that the renewable fraction of the Italian economy declined and keeps declining. The Brazilian ELR increased at a slower rate, from 0.95 (year 1981) to 4.99 (year 2008). The Brazilian economy is still based on a large renewable and local resource basis, while developed countries, like Italy, are generally characterized by nonrenewable and imported resource use.

*Trade assessment*

In order to have a deeper understanding of economic relations and differences between the two countries, an evaluation of trade involving Brazil and Italy was also performed, related to the most recent year for which data are available (2008). Table 12.10 shows the economic value, the quantity and the associated emergy flows of selected products commercialized between the countries.

According to Table 12.10, Brazil exported a total amount of 1.50E+13 g of products to Italy, and imported 8.04E+11 g in the year 2008, equivalent to respectively US$ 4.77E+09 of exports and US$ 4.61E+09 of imports, thus showing a conventional term of trade approximately equal to one. Instead, in terms of emergy of the selected products, Brazil exported 5.68E+22 seJ/yr while only importing 1.78E+21 seJ/yr, three times more exported emergy than received. The higher emergy exported by Brazil may be explained in terms of higher purchasing power of the Italian currency and the very low market price of primary resources that constitute the largest fraction of Brazilian exports. Considering that the emergy value not only includes the actual amount of raw material that constitutes the resource, but also the indirect environmental inputs that are "embodied" in the resource itself (groundwater, topsoil, environment as a source and a sink, technology and know-how; Bargigli et al., 2004) but have no market value, a huge concern emerges from the fact that resources and environmental integrity are exported at low cost and without significant advantage to the country.

Table 12.10: Selected products traded between Brazil and Italy in 2008

| Products | Amount (g) | Economic Value (US$) | UEV [A] (seJ/g) | Ref. | Emergy w/o L&S (seJ/yr) | Emergy of services [B] (seJ/yr) | Emergy with L&S |
|---|---|---|---|---|---|---|---|
| **Brazil to Italy** | | | | | | | |
| Soybeans | 1.13E+12 | 4.77E+08 | 9.87E+09 | [a] | 1.12E+22 | 1.23E+21 | 1.24E+22 |
| Coffee grains (non-toasted) | 1.73E+11 | 4.77E+08 | 2.57E+10 | [b] | 4.45E+21 | 1.23E+21 | 5.68E+21 |
| Round-wood | 7.45E+11 | 4.15E+08 | 6.79E+08 | [c] | 5.06E+20 | 1.07E+21 | 1.57E+21 |
| Iron ore agglomerated | 4.10E+12 | 3.79E+08 | 2.22E+09 | [d] | 9.09E+21 | 9.74E+20 | 1.01E+22 |
| Iron ore non-agglomerated | 6.68E+12 | 3.13E+08 | 2.22E+09 | [d] | 1.48E+22 | 8.04E+20 | 1.56E+22 |
| Leather | 1.98E+10 | 2.06E+08 | 2.42E+11 | [e] | 4.80E+21 | 5.29E+20 | 5.33E+21 |
| Refined copper cathodes | 2.28E+10 | 1.59E+08 | 3.36E+09 | [f] | 7.66E+19 | 4.09E+20 | 4.85E+20 |
| Bagasse | 3.73E+11 | 1.39E+08 | 1.97E+08 | [g] | 7.33E+19 | 3.57E+20 | 4.31E+20 |
| Shoes | 2.72E+09 | 1.21E+08 | 7.22E+09 | [h] | 1.96E+19 | 3.11E+20 | 3.31E+20 |
| Corn grains | 3.21E+11 | 7.22E+07 | 1.45E+10 | [a] | 4.66E+21 | 1.86E+20 | 4.85E+21 |
| **Total of selected products** | **1.36E+13** | **2.76E+09** | | | **4.97E+22** | **7.09E+21** | **5.68E+22** |
| Total of all products traded [C] | 1.50E+13 | 4.77E+09 | | | | | |
| **Italy to Brazil** | | | | | | | |
| Parts for tractors and vehicles | 1.48E+10 | 1.36E+08 | 4.65E+09 | [i] | 6.89E+19 | 1.93E+20 | 2.62E+20 |
| Lubricants without additives | 8.25E+10 | 1.00E+08 | 3.38E+09 | [j] | 2.79E+20 | 1.42E+20 | 4.21E+20 |
| Parts for vehicles' body | 1.32E+10 | 9.41E+07 | 4.65E+09 | [i] | 6.14E+19 | 1.34E+20 | 1.95E+20 |
| Parts of mach. for earth-moving | 1.94E+10 | 7.74E+07 | 4.65E+09 | [i] | 9.03E+19 | 1.10E+20 | 2.00E+20 |
| Gear for vehicles | 4.05E+09 | 6.72E+07 | 4.65E+09 | [i] | 1.88E+19 | 9.54E+19 | 1.14E+20 |
| Beta interferon | 3.65E+06 | 5.59E+07 | 4.25E+10 | [k] | 1.55E+17 | 7.94E+19 | 7.95E+19 |
| Naphthas for petrochemical | 5.35E+10 | 4.54E+07 | 4.65E+09 | [l] | 2.49E+20 | 6.45E+19 | 3.13E+20 |
| Machinery for packaging | 8.71E+08 | 4.27E+07 | 4.65E+09 | [i] | 4.05E+18 | 6.06E+19 | 6.47E+19 |
| Other machinery | 1.87E+09 | 4.20E+07 | 4.65E+09 | [i] | 8.70E+18 | 5.96E+19 | 6.83E+19 |
| Pharmaceutical drugs | 7.25E+07 | 4.15E+07 | 4.25E+10 | [k] | 3.08E+18 | 5.89E+19 | 6.20E+19 |
| **Total of selected products** | **1.90E+11** | **7.02E+08** | | | **7.83E+20** | **9.97E+20** | **1.78E+21** |
| Total of all products traded [C] | 8.03E+11 | 4.61E+09 | | | | | |

Source: Brazilian Ministry of Development, Industry and Commerce (MDIC, 2008)

[A] Unit Emergy Value (all values updated to the 15.83E+24 seJ/yr baseline and do not include labor and services).

[B] Emergy of services estimated using the emergy to money ratios calculated in this work for Brazil and Italy. In the case of a product exported from Brazil to Italy, we have used the Brazilian emergy to money ratio calculated for 2008 (2.57E+12 seJ/US$). In the case of an Italian product being exported to Brazil, we have used the Italian emergy to money ratio calculated for 2008 (1.42E+12 seJ/US$).

[C] includes all products traded, not only the selected ones.

References: [a] Brandt-Williams, 2002; [b] Guillén, 2003 (value of 1.54E+06 seJ/J= 1.54E+06 seJ/J x 4,0 kcal/g x 4186 J/kcal= 2.57E+10 seJ/g); [c] Bastianoni *et al*., 2001; [d] Buranakarn, 1998 (estimated as iron ore); [e] Odum *et al*., 1987a (value of 1.44E+07 seJ/J= 1.44E+07 seJ/J x 4,0 kcal/g x 4186 J/kcal= 2.42E+11 seJ/g); [f] Lapp, 1991; [g] Odum and Odum, 1983; [h] Odum *et al.,* 1987b (estimated as rubber); [i] Haukoos, 1995 (estimated as steel products); [j] Odum, 1996 (estimated as crude oil); [k] Odum *et al*., 2000 (estimated as fertilizer); [l] Haukoss, 1995.

The emergy of services represents a large fraction of the traded flows if highly manufactured goods are dealt with. This can be clearly observed in Table 12.10: the emergy related to labor and services (presented as a column) is a large share of the emergy of items exported from Italy to Brazil, since they are highly industrialized and manufactured goods. Taking the beta interferon (chemical product with a high aggregated value) as an example, the raw emergy (not accounting for labor and services) is 1.55E+17 seJ, whereas the emergy related to the human services is 7.94E+19 seJ. On the other hand, as already mentioned, Brazilian products exported to Italy are primary or semi-manufactured, therefore the emergy share related to the human services is not large compared to the total emergy of the product.

Results provide different typologies of information. First of all, they allow an understanding of what are the most important sources of support to a country's economy and how they relate to physical, demographic and economic parameters; secondly, the allow a picture of the evolution of important aspects of each national economy over time, in so highlighting the ongoing changes; thirdly, they help identify the crucial issues (bottlenecks, strategic resource management) to be included in concerned policy making; and finally, they shed light on aspects of fair trade between countries, for implementation of new and more equitable trade strategies. The latter aspect suggests that market values should no longer be the main benchmark and reference basis for trade, and that the old neoclassical economic criteria that regulate international markets are no longer suitable for a sustainable globalized economy.
Concerning the above points, Tables 12.3 and 12.5 suggest a variety of important aspects:

1) the Italian economy if fully nonrenewable (only 4 % renewable) while the Brazilian economy receives 17 % of its support from renewable sources. Since the amount of renewable emergy in a country cannot be increased (depending on environmental constraints), the only way for a national economy to be more sustainable is decreasing both the local and the imported nonrenewable emergy: this can be done by means of efficiency policies, by more sustainable lifestyle policies, and by increasing recycle patterns. Of course, "size" aspects like population, buildings, infrastructures, also have an important impact on emergy demand, but they are more difficult to decrease in the short run.
2) Trends of emergy based indicators suggest both countries evolving towards decreased share of renewables, larger use of nonrenewables, larger emergy per capita, larger environmental loading and lower sustainability, as expressed by the ESI values in Tables 12.3 and 12.5. While the trend towards decreased sustainability cannot be denied in both countries, the Brazilian situation is still much better than the Italian one. There is, however, a clear tradeoff between economic development and higher income per capita and environmental sustainability. The latter declines when traditional economic indicators rise up. It is undeniable that the present development policies in both countries and the need to keep high economic performance are affecting the environmental integrity, by increasing resource and land pressure. The decrease of sustainability indicators has been so fast in the last 20 years that the most suitable time to implement economic policies that are capable to invert the trend is now. Any further delay would make the situation even worse and maybe irreversible.
3) The total amount of emergy actually used (i.e., the total environmental support directly and indirectly received by a given country) provides a measure of the real size of a country's national economy in the larger frame of the ecosphere. According to Table 12.3, the total emergy use steadily increased in Brazil up to 1.8 times in the investigated period, at an average rate of about 4.1% per year (Figure 12.4). Its PPP GDP (Gross Domestic Product expressed in terms of Purchasing Power Parity) increased yearly by 15.7%, while its PPP GDP per capita increased by 9.2% (Figure 6a). Instead, the Italian emergy use increased by 13.4% yearly until the year 2000, then stabilized at values more or less 5% lower in the last 8 years (Figure 6b). Figure 6 also indicates a decreasing emergy to money ratio in Brazil until the year 2000, with a small increase

in 2008, and a quite stable decrease trend for Italy, with a sharp decrease after the year 2000. In Brazil the increase of emergy use is linked to the increase of imports of fuels, minerals, and electricity, which are directly related to the higher consumption and increasing industrial activities in the country. Instead, the declining trend observed for Italy is related to the economic crisis, the consequent decline on the use of oil, but also energy efficiency measures. In general, countries over a development pattern show an increasing GDP and a decreasing emergy-to-money ratio. The GDP increase in Figures 12.5a and 12.5b is not due to inflaction, since we are relying on PPP GDP instead of conventional GDP. Therefore, diagrams correspond to a real increase of purchasing power and potential availability of goods. What is the meaning of the declining emergy-to-money ratio? The decline of the emergy-to-money in Brazil until the year 2000 indicates that the GDP growth has been faster than the increasing emergy use (Figure 12.4) or, in other words, that the efficiency of GDP generation through emergy investment decreases when a society shifts from subsistence to developed status (more emergy is invested to generate a unit of GDP in developed societies, with less marginal GDP increase per unit of invested resource). In 2008, Brazil had an enourmous increase (almost double) on the imports and on the use of local nonrenewables in terms of emergy, therefore, surpassing the GDP increase rate, leading the emergy-to-money ratio to a small positive variation in the most recent investigated years. In comparative terms, Italy only used about 1.00-2.00E+12 seJ to generate one US$ of economic product in the most recent years, while Brazil invested about 3.00-2.00E+12 seJ to reach the same result. Considering that GDP is measured in PPP terms, the Italian economy has been more efficient in GDP generation than was Brazil, in spite of the continuous growth of the Brazilian economy in the investigated period.ratio

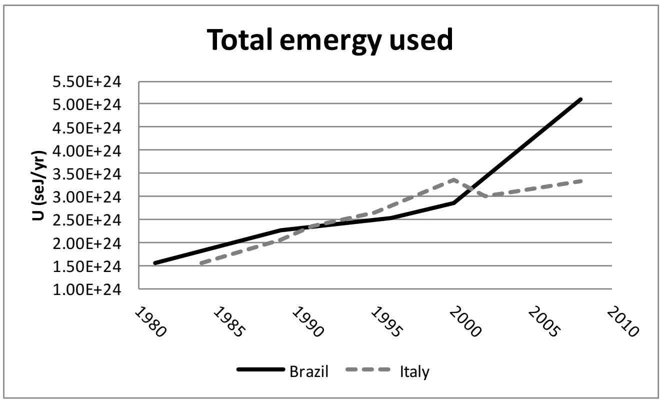
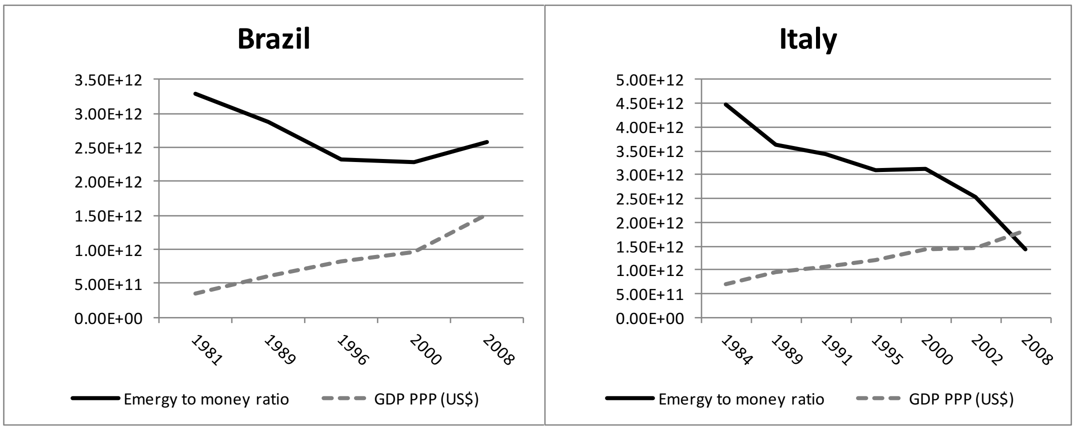



*Figure 12.4. Total emergy used U (seJ/yr) in Brazil and Italy.*




*Figures 12.5a,b. Trends of PPP GDP (US$) and Emergy-to-money ratios in Brazil and Italy*

When analyzing Figure 12.6, emergy use per person, the situation is reversed, with Brazil ranking much lower than Italy. The Brazilian emergy used per capita shows a stable trend until 2000, when it starts increasing, because emergy use increased at a rate much higher than population. Italy always had an increasing trend during the period investigated, with a small decline around the year 2000. This can be explained by the combined effect of different population growth patterns and different life styles in the two countries as well as higher trade benefits to Italy.

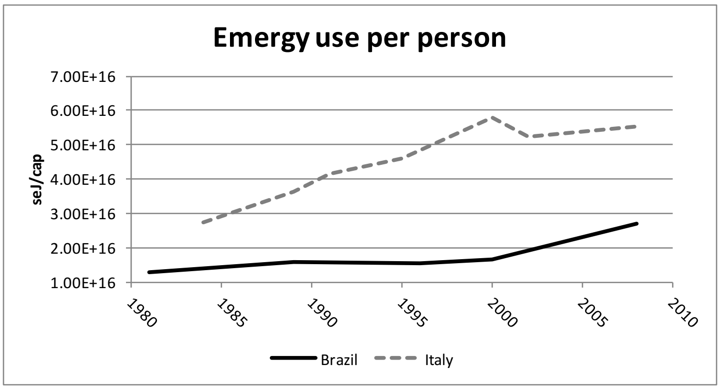



*Figure 12.6. Emergy use per person in Brazil and Italy*

Emergy density (seJ $m^{-2}$) presented in Figure 12.7 shows the areal concentration of the emergy use, which can be a useful indicator of the intensity of activities in the country. The 2008 emergy density is 5.51E+11 seJ $m^{-2}$ in Brazil and 1.10E+13 seJ $m^{-2}$ in Italy, about 20 times higher in Italy. This is a clear indicator of land as a limiting factor: the need to keep economic activities ongoing (e.g. in the construction sector: roads, buildings, viaducts, high speed train) devours the landscape and requires new developments be implemented day-by-day, by investing resources much beyond the land-based carrying capacity of the country. Brazil is still buffered by the large availability of undeveloped land. Brazilian emergy density is very low and constant if compared to the always-increasing Italian values. Brazilian lower density is due to the large amount of land available, but the word "available" should not be misinterpreted. This is not land available for any use, but instead it is buffer land already used in support of the present Brazilian economy, in so reinforcing the country's carrying capacity (Brown and Ulgiati, 2001). Converting this land to economic uses would increase GDP, but would also decrease the overall carrying capacity and sustainability.

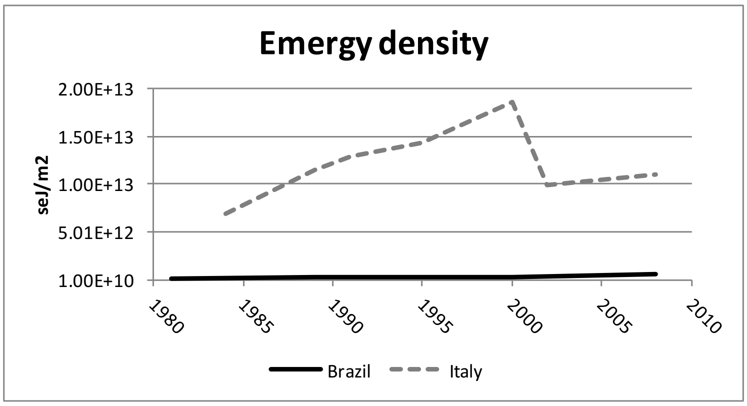



*Figure 12.7. Emergy density in Brazil and Italy*

When analyzing figures 12.8a and 12.8b, it becomes clear that Brazil is much less dependent on imported economic resources (lower F/U) than Italy. It uses more renewable resources (higher R/U) and more local resources (both renewable and nonrenewable) than Italy in relation to the total emergy use of the country. The 2008 fraction of imported emergy is 32 % in Brazil and 73 % in Italy. This points out an inner fragility of Italian economy, with its large dependence on outside sources. Until Italy is able to acquire primary resources from international markets, its ability to manufacture these resources and make higher added value products translates into an economic advantage, thanks to the higher purchasing power of its currency. When strategic resources (fossil fuels, rare earths) become less available due to international demand by emerging countries and geopolitical constraints, including increasing market price due to competition, it may be increasingly difficult to Italy to keep the strategic position it used to have in the past and its economy may start declining and losing importance.

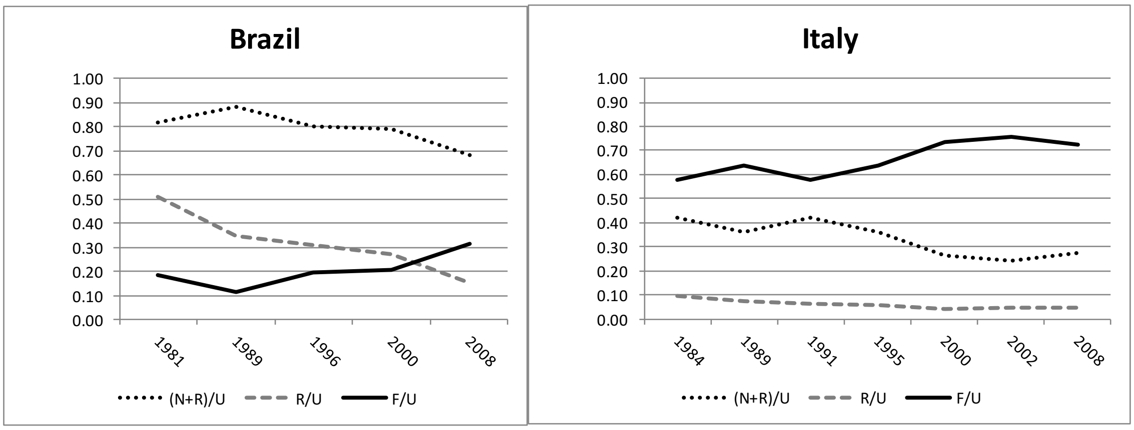



*Figure 12.8a,b. Emergy flows in Brazil and Italy*

Figures 12.9a and 12.9b show a comparison among the main performance indicators calculated for Italy and Brazil. The Emergy Yield Ratio (EYR= U/F= (R+N+F)/F), a measure of the ability of a process to exploit and make local resources available by investing outside resources. The lowest possible value of EYR is 1, by definition. For such a reason, the decreasing value of the indicator over time for both countries indicates systems that decrease their ability to rely on local resources. In both countries the increased emergy use is due to larger use on nonrenewable local resource and imported goods, but the locally renewable resources are so high for Brazil compared to nonrenewable and non-local sources that the Brazilian EYR still was 3.15:1 compared to a low 1.38:1 for Italy in the last year investigated.

The Environmental Loading Ratio (ELR= (N+F)/R) calculated for the Italian system is very high (reaching a value of 21.28 in the year 2008), indicating a much higher dependence from non-renewable resources. Instead, the medium Brazilian ELR (5.48 in the year 2008) points out a great reliance on renewable inputs. The two parameters combined together provide the Emergy Sustainability Index (ESI=EYR/ELR), an aggregate measure of economic and environmental performance that is much lower for the Italian system than for Brazil. ESI for the Italian system decreases steadily by more than 45% (0.06 in year 2008). Same decreasing trend is observed in Brazil, but the absolute value is higher.

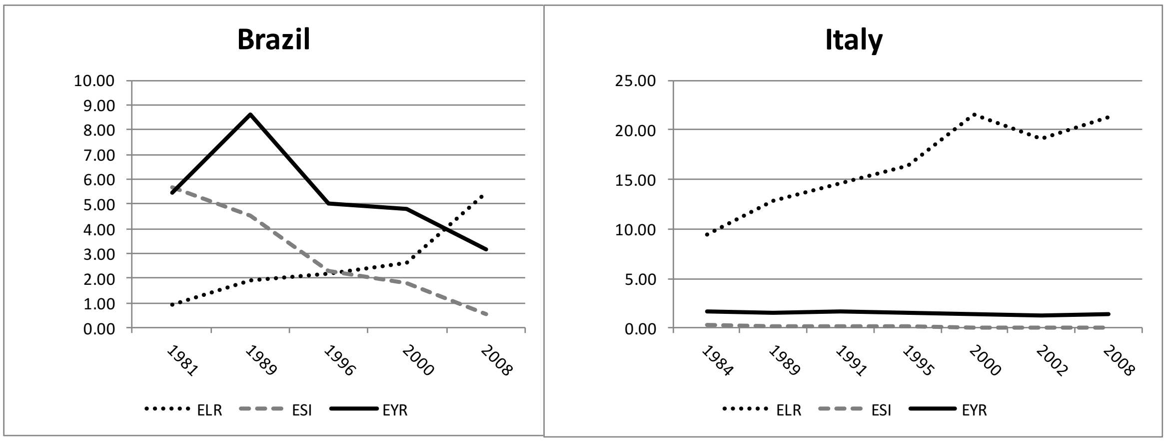



*Figure 12.9a, b. Emergy indices for Brazil and Italy*

*Trade unbalance*

“Terms of trade” is defined as the relationship between the price received for exports and the amount of imports a country is able to purchase with that money as: terms of trade is equal to the ratio “total economic value of exports/total economic value of imports”. It can be useful to show the level of a country’s economic dependence on imports, but it doesn’t really show the quantity (or mass amount) or quality traded, since price is highly influenced by inflation rates, taxes, technology, and the purchasing power of a country’s currency.
According to Lomas *et al.* (2007), since money only pays for the human labor and services, it is highly unlikely that market price can take into account the “hidden imports” embodied in the produtcs. Emergy synthesis provides instead an alternative definition for “terms of trade”, whereby the emergy associated to the traded resource is compared to the emergy associated to the money received. Each traded product is multiplied by its emergy intensity factor (transformity, seJ/J, or specific emergy, seJ/g). The total emergy exported with the traded raw resources is then compared to the total emergy imported with the commodities that can be purchased on the international market thanks to the money received.
Figure 12.10 shows that Italy is much more dependent on imports in terms of emergy than Brazil, although there is a tendency of reduction in the Italian case. As a developing nation, Brazil is importing more in terms of amount and also aggregated value, therefore there has been a tendency of increasing on the imports/exports ratio since 2000.

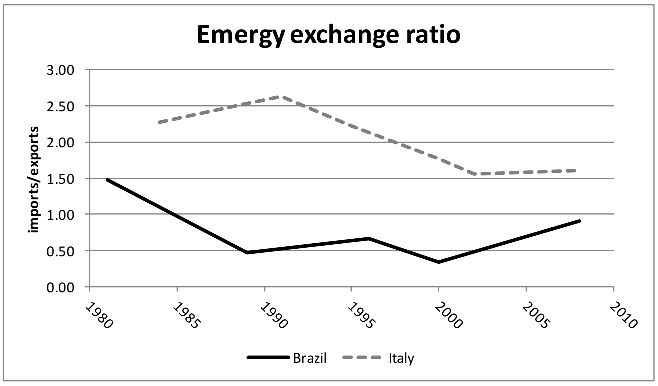


*Figure 12.10. Emergy exchange ratio (imported emergy/exported emergy) in Brazil and Italy*

The application of the Emergy method to traded products in Table 12.6 shows a very different perspective on trade balance. Brazil exported 5.68E+22 seJ (4.97E+22 seJ not accounting for labor and services) to Italy and only received (for the same economic value) 1.78E+21 seJ (7.83E+20 seJ not accounting for labor and services) in 2008 considering top traded products. It means that Brazil receives an average of US$ 5.55E-14 (not accounting for labor and services) and US$ 4.86E-14 (including labor and services) per seJ of commodity exported (or, in other words, invests between 1.80E+13 seJ (not accounting for labor and services) and 2.06E+13 seJ (including labor and services) to generate an income of US$ 1). Whereas Italy receives between US$ 3.94E-13 (including labor and services) and 8.97E-13 US$ (not accounting for labor and services) per seJ of product exported to Brazil (or invests between 1.12E+12 and 2.54E+12 seJ per US$ gained).

If we analyze this trade only in terms of total monetary value (in US$), it would be considered as a “fair-trade” since Brazil’s export/import equals 1.03. When considering the amount of traded products (mass), it becomes clear that Brazil exports ten times more than imports from Italy. This happens, because Brazilian exportation is based on bulk resources that are supplied without qualitative differentiation across the market. Observing the emergy flows for selected products traded between Brazil and Italy, a huge disparity in the trade is shown: Brazil’s exports emergy/imports emergy equals 63.47 (not accounting for labor and services) or 31.91 (including labor and services). Since the monetary value of the trade between Brazil and Italy is almost the same, this suggests that the economy of Italy is much more supported by resources from Brazil than money flows indicate.

*China*

The first emergy evaluation of China was performed by Lan and Odum (1994); updates were published by Yan (2001) and Lan et al. (2002). Finally, most recent evaluations and past time series were provided by Jiang et al. (2008), Yang et al. (2010) and Zhang et al. (2012). In particular, Yang et al. (2010) provided an impressive set of data over a 1978-2005 time span. The University of Florida Center for Environmental Policy also published a very accurate emergy evaluation of China in the year 2000 within its National Environmental Accounting Database (NEAD, 2011), and further update is in progress.

The real problem with this very interesting time series of values is their reliance on different sources of data (not in full agreement to each other) and their lack of standardization. The procedures and emergy-based conversion factors (Unit Emergy Values, UEV; see below) used in earlier papers have been modified and improved in the most recent years (Odum et al., 2000; Brown and Ulgiati, 2010; Brown et al., 2011), leading to significant changes and difficult comparability of published values. In this paper we perform an emergy evaluation of the

Chinese economy in the year 2009, and aim at comparing our findings with the previous published results. In order to make the comparison possible, we have standardized the previous calculation procedures, in order to use consistent UEVs, the same biosphere reference emergy baseline (Odum et al., 2000), the same list of calculated indicators (Brown, 2010), the same source for GDP at current price and $/RMB conversion ratio (The Chinese University of Hong Kong, 2000; X-Rates.com, 2011; Trading Economics, 2011), and the same calculation procedures. We did not make any significant alteration of input data, except in a few cases where data did not match the referenced source (e.g. the emergy and money values of import and exports in Lan and Odum, 1994, as well as the GDP values in Yang et al., 2010, showing a declining instead of an increasing trend). We also made a few corrections to the published data, where we identified computational inaccuracies or mistakes likely to affect the final indicators (e.g.: Yang et al., 2010, Table 2, show a 3-times GDP decrease from 1978 to 2005, which is incorrect and affects the Emergy/GDP ratio of China in Table 4). In so doing, we generated consistent time series of emergy use and emergy performance indicators for China from the year 1978 to the year 2009 and shed light on the economic and environmental performance of the country over time.

When discussing the results of an emergy evaluation of a country or process, we should abandon the usual categories of energy and mass flows and storages. Emergy accounting has a different meaning, in that it refers to the efforts displayed by nature to generate the resources over time. The emergy values of fuels and mineral used in a process account for the convergence of environmental processes (solar, gravitational, geological, photosynthetic, and metabolic) over time and space, thus bringing into the assessment concepts of systems ecology, renewability, natural selection and resource quality. The results of such an assessment can be, and they actually are, surprising and very different than those from conventional energy, mass or money assessments.

A second important premise is that the unprecedented performance of Chinese economy over time cannot be understood by means of the linear growth categories that are generally used to describe growth in western countries. Indeed, the growth of Chinese GDP and emergy use, as well as of several other performance indicators are hardly described even in terms of exponential growth. The doubling time $T_d$ of any asset A that grows exponentially at an annual rate of x%, is roughly calculated (Weisstein, Eric W., 2012) as:

$$T_d = (\log 2)/\log (1+x/100) \approx 72/x$$

In the last 20 years, the average China's annual economic growth rate has been around 10%, thus yielding a doubling time equal to 7 years, approximately. This means that the "size" of the Chinese economy has doubled many times in the investigated period, which never happened in any other world economy of comparable size. Population did not follow a similar exponential dynamics, only growing by 39% in the entire investigated period (Figure 1), with decreasing growth rates over time, due to other limiting factors and governmental policies. Instead, both emergy use and environmental pressure increased exponentially, as detailed later in this paper, generating support to growth and, at the same time, environmental concerns. Performance indicators must therefore be discussed in the light of fast growth, resource availability and resource quality factors.

*Country's emergy use*

The total country emergy use, U, increased by 5.6 times in the investigated period (Figure 12.11). This increase was due to an increased use of local mineral and nonrenewable energy resources, N, as well as of slow-renewable resources such as topsoil and water storages (Table 12.7, items 5a,5b). Fishery extraction (catch exceeding annual turnover) (Die and Caddy, 1997; FAO, 2005, 2010; UNEP, 2007) was also included as a slow-renewable emergy flow, while forestry extraction was not, due to successful reforestation policies (wood withdrawal being less than re-growth) (Piao et al., 2005; FAO, 2007; Cui, 2010). Increased imports of fuels, minerals, goods and services also significantly contributed to the increased annual emergy use. Renewable sources, R, (item 4 in Table 12.7) include - by definition - the total renewable emergy inflows to the country, not only the amount of solar energy captured by technological devices such as photovoltaic or wind modules. The latter can be increased (by increasing the technological effort), while the former (total emergy, R) remains constant (Brown and Ulgiati, 2011). In the year 1978, the fraction of renewable resources (item 12 of Table 12.7) was 46% of total emergy use in the same year. This fraction declined steadily down to a low 9% in the year 2009 due to larger nonrenewable uses. This means that the present economic development of China is due to, and heavily depends on, large use of local and imported nonrenewable resources (fuels, coal, minerals) (Figure 12.11). In particular, although the absolute amount of fossil fuel use increased steadily in the investigated period (in both energy and emergy terms), the percentage of emergy use that is fossil fuels decreased in the most recent years due to a parallel faster increase of minerals, which also contributed to the increase of total emergy U.

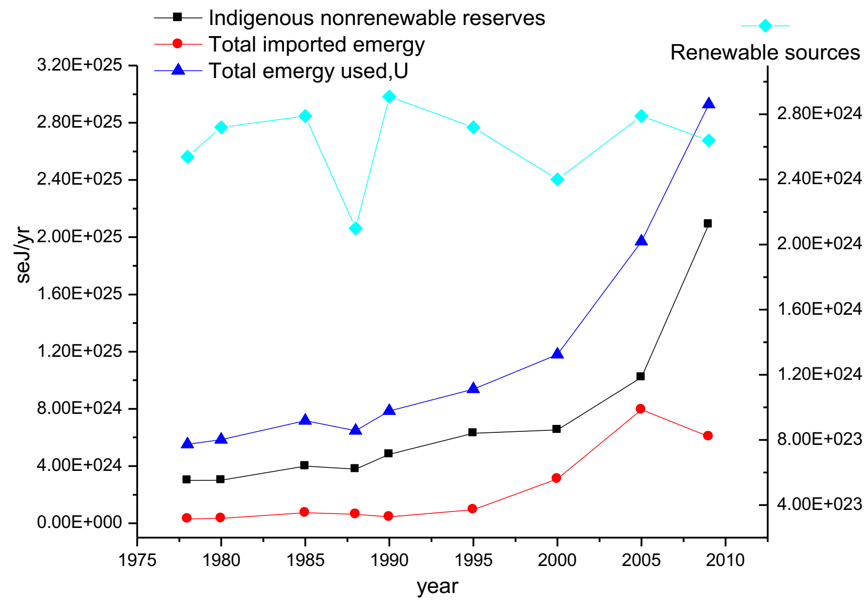



**Figure 12.11. Trends of renewable, nonrenewable, imported and total emergy use in China.**

*Emergy and Gross Domestic Product*

The trend of Chinese GDP is shown in Figure 12.12, expressed as both US $ and Yuan RMB (Table 12.7, items 3a,3c). In spite of the increasing and fluctuating RMB/$ Exchange Ratio (Table 12.7, item 3b), GDP shows an impressive increasing trend, no matter the currency used, specially in the last 20 years. The GDP growth seems smaller when expressed in $, because of the increasing $/RMB exchange ratio.

The trend of the emergy/(nominal GDP) ratio for China is shown in Figure 12.12 expressed as both seJ/$ and seJ/Yan RMB (Table 12.7, items 19a,19b). Both curves show a declining trend, as expected with countries that undergo a development of their economy (in general, because total emergy use grows slower than total money circulation). The average emergy/GWP (Table 12.7, item 18) shows a smaller absolute value and a declining trend, mainly due to the overwhelming presence of data from developed countries in the average calculation procedure. The Purchasing Power Ratio, defined as $(emergy/GDP)_{China}/(emergy/GDP)_{world}$, shows a declining trend: the same expense of 1 dollar purchased 8.26 times more emergy in China than in the average world market in the year 1978, while in 2009 the gap decreased to 2.9:1. This means, however, that one dollar spent in China in the year 2009 still buys 3 times more emergy than in the average world market. This means that China sells cheap emergy to the world markets and purchases less-emergy expensive commodities from developed countries.

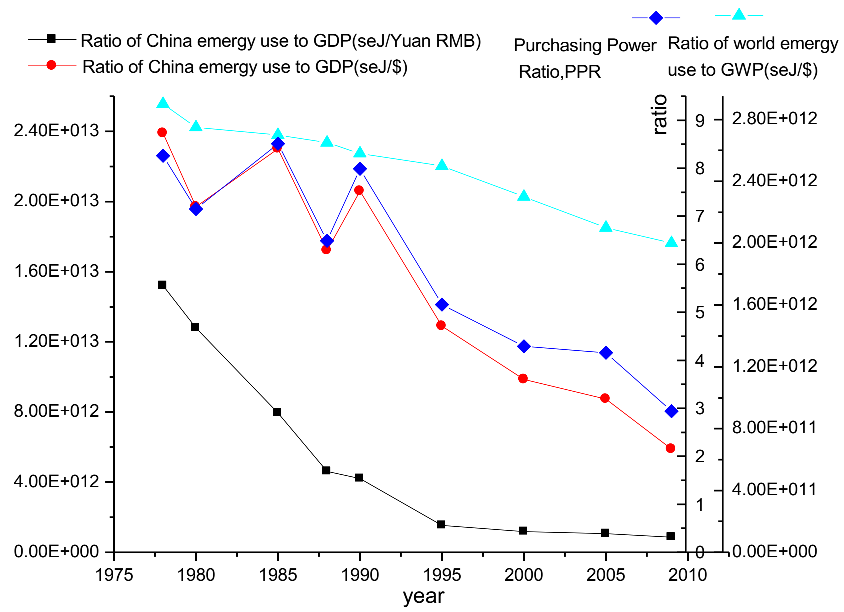


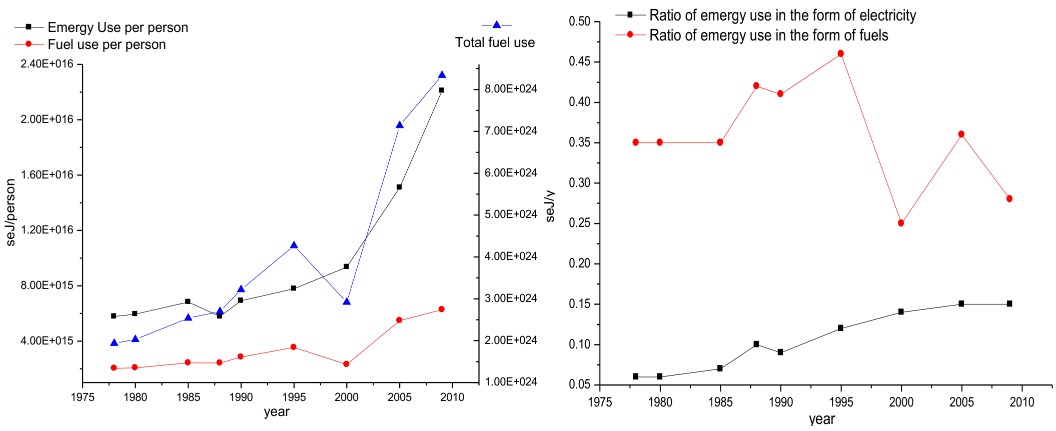

**Figure 12.12. Left axis: Emergy/GDP ratio over time in China and worldwide (average values). Right axis: Purchasing Power of China relative to the world average.**

*Emergy and land*

The increase of total emergy use at country level translates into a parallel 5.6-times increase of the areal pressure, as expressed by the Empower Density (Table 12.7, item 14). Such indicator (total emergy invested per unit area per year) suggests land as a potential limiting factor to further development and land-use intensity change as a potential risk for natural capital integrity in China. In fact, while the renewable empower density (renewable emergy divided by area) is costantly in the order of 2.44 E+11 seJ $m^{-2}$ $yr^{-1}$, the nonrenewable empower density steadily increased up to 2.70 E+12 seJ $m^{-2}$ $yr^{-1}$. Brown and Vivas (2005) identified the nonrenewable empower density as the basis for the construction of a Landscape Development Intensity index (LDI), to be used as a measure of the human disturbance gradient (the level of human induced impacts on the biological, chemical, and physical processes of landscape). Although these authors suggest the LDI be used for the assessment of local impacts (e.g., for the USA: row cropping, 1.07 E+12 seJ $m^{-2}$ $yr^{-1}$; high intensity agriculture, 13.5 E+12 seJ $m^{-2}$ $yr^{-1}$; average industry 52.1 E+12 seJ $m^{-2}$ $yr^{-1}$), the use of the same indicator at country level provides a benchmark for comparison of local development to country's average as well as a way to monitor intensity change over time. The present nonrenewable empower density of China is about 11 times higher than the renewable empower density.

*Emergy and population*

The relation of emergy use and population translates into an indicator of emergy use per person per year (Table 12.7, item 15). This indicator (an average measure of per-capita resource availability in support of potential development and standard of life) increased 4 times from 5.78E+15 seJ person$^{-1}$ yr$^{-1}$ to 2.21E+16 seJ person$^{-1}$ yr$^{-1}$. It should be observed that per-capita availability of emergy is an average value applicable at country level and does not mean an actual availability to each person nor that this emergy is appropriately used to increase the individual standard of life (will substitute “availability with “use”). Emergy (i.e., resources) can be used efficiently and effectively in so reaching the intended goal of production and consumption at low resource intensity, but it can also be used through inefficient processes that increase the production cost at the expense of achievable quality of life. When resources are scarce (for example, as fossil fuels seem to be at present) sustainability is maximized by increased efficiency, according to the Maximum Empower Principle (Lotka, 1922a,b; Odum and Odum, 2001). Therefore, the increased emergy per capita in Figure 6 suggests a potential, not yet actual, improvement of the average standard of living of Chinese population, leaving room to efficiency and more-from-less strategies. That a potential improvement of the standard of life is gradually occurring is confirmed by the parallel increase of the fraction of emergy use that is electricity (from 6% in 1978 to 15% in 2009; Table 3, item 21), due to increased use in both household and industrial sectors. Electricity is a special commodity that is strictly related to the standard of life, since its use is linked to more modern industrial processes, increased use of informatic devices and networks, widespread household appliances (TV’s, air conditioning, etc). A similar rationale applies to the increasing use of fossil fuels (Table 12.7, items 22b,22c), in support of electricity production and other industrial and urban uses (vehicles, machinery, domestic heating) (Figure 12.13a,b).




6.a 6.b

**Figure 12.13. Emergy use per person and fuel use per person per year in China (figure 6.a, left axis); total fuel use (figure 12.13.a, right axis); percentages of electric and fuel use (figure 12.13.b); all expressed in emergy terms.**

A direct consequence of the link between emergy use and average standard of life is clearly expressed by the comparison between renewable and nonrenewable carrying capacity at present standard of life of China, compared with the past (Figure 12.14; Table 12.7, items 16 and 17). In the year 1978, the population that could be supported by local renewable sources (at the 1978 average living standard implicit in the lower total emergy use per capita; item 16 of Table 3) was 439 million people. Instead, in the year 2009, the combined effect of increased emergy use, related increase of standard of life, increased population and increased fraction of nonrenewable sources, translates into only 116 million people potentially supported by renewables. On the other side, the population exceeding the renewable carrying capacity in 1978 was 517 million people (at the 1978 standard of life) while 1,210 million had to be supported in the year 2009 by nonrenewables. It clearly appears that it is the nonrenewable emergy that allows the coupled increase of population and standard of life in China. In more developed and industrialized countries, with high standard of living supported by nonrenewables, de-growth strategies are presently being proposed, in order to decrease resource use and pollution. These strategies are less likely to be suitable for China at its present stage of development, with large fractions of population striving to reach a more acceptable standard of life. As a consequence, a more gradual approach is needed to balance the interplay of resource availability, environmental protection and development. If China is to become more sustainable from an environmental point of view, there are three alternatives ahead: decrease or at least stabilize population (a result already partially achieved and hardly improvable), decrease the standard of life (a result absolutely unpopular and unlikely at present), or increase the efficiency of nonrenewable emergy use, while at the same time trying to keep the standard of living unchanged. The latter seems to be the only likely strategy for China in the future years, through further technological development and choice of moderate lifestyles.This strategy should be coupled to a search for new ways to wellbeing, not based on western consumerism, but instead based on quality; not aimed at faster degradation of resources for non-durable wealth, but instead based on better use of resources through less consumerism, durability, community services.

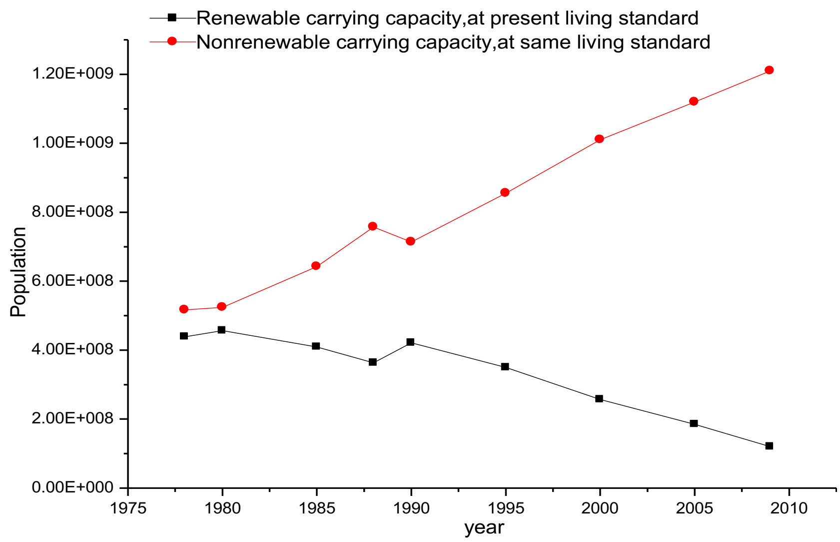



**Figure 12.14. Trend of population supported on renewable and nonrenewable emergy, at the average standard of living in each year.**

***Emergy and trade***

Trade has been and still is an important activity sector for China. Since the 70’s, after the improvement of diplomatic and commercial relations between China and the Unites States, trade of China with Western foreign countries increased quickly, based firstly on export of low labor-cost manufactured goods and raw resources (of which China is rich), and then also on high-technology products, often within partnership agreements with Western companies willing to invest in China. Most recently, the situation is facing a reversal trend, with China in turn very active with financial investments in the USA and Western countries. No doubt, the

increase of China's trade all over the world is an important component of the country's economic development. In most recent years, the increase of Chinese standard of life also generated an increase of imports of food items, oil, chemicals and commodities. China's 2009 trade can be summarized by a total amount of 1.20E+12 US $ of exports (China Statistical Yearbook, 2011) versus a total amount of 1.01E+12 US $ of imports, with a monetary terms of trade ratio of 1.20, the highest terms of trade in the investigated period following the oscillating trend depicted in Figure 12.15. The trade of China can also be looked at under an emergy perspective, namely under the point of view of resources trade, not money. In spite of the common belief that exports are always good because they provide a money flow to the exporting country according to market demand, the trade advantage of a nation may not rely on the money flows, but instead on the net emergy inflow (emergy of imports – emergy of exports) capable to provide increased support to the inside economy and jobs. In other words: (a) the money received for exports is 20% larger than the money paid for imports (2009 money-based terms of trade= 1.20:1), but (b) the emergy exported is much larger than imports, so that the Chinese 2009 emergy-based terms of trade (EER, Emergy Exchange Ratio) (Bargigli et al., 2004) was 1.74 in 2009, showing an unbalance in terms of actual resource flows. It should be noticed, however, that in the year 1990 the economic terms of trade was 1.16, similar to the years 2005 and 2009, while the emergy exchange ratio was much higher than in recent years, signalling that China is improving its trade behavior, by sending out less emergy per unit of import than in the past, for the same economic benefit. In other words, China is learning how to generate a larger economic advantage per unit of resources exported. Processing raw resources at home and sending out higher quality manufactured goods is a good policy that supports economic growth, self-reliance and domestic jobs: from this point of view, the reliance of China on local resources is still large (79%, Table 12.7, item 13), although slowly declining compared to previous years.
From a trade point of view, a declining trend of the emergy/GDP ratio is beneficial to a country's economy, in that it decreases the emergy that is embodied in services associated to exports and contributes to decrease the EER unbalance.

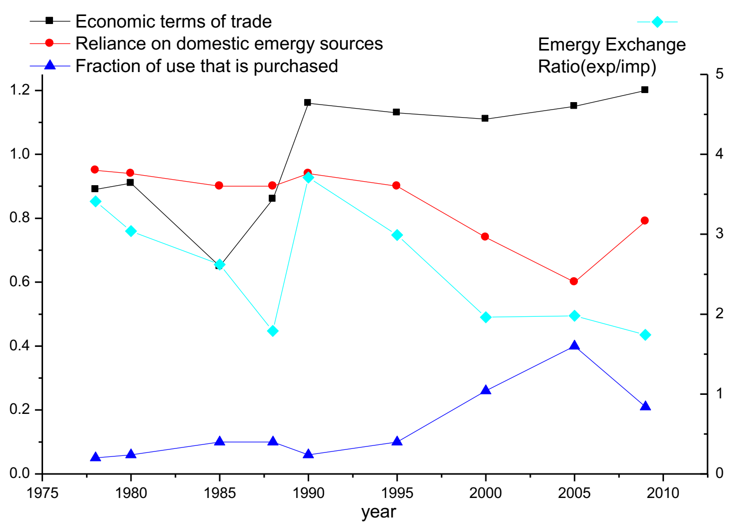



**Figure 12.15. Left axis: Economic Terms of Trade, Reliance on domestic emergy sources, Emergy Exchange Ratio, Fraction of use that is imported. Right axis: Net Trade.**

***Country Sustainability Assessment***

Sustainabily is a complex concept based on assessing economic, environmental and social aspects together. The emergy concept encompasses all of these aspects. The economic performance, within a market perspective, is accounted for through the inclusion of money flows of labor as well as services associated to imports and exports, evaluated as such (in currency terms) and then converted to emergy units. The environmental aspects are captured by the expansion of scale to include the biosphere work (time and spatial scales) for resource generation, in a supply-side perspective as well as by indicators of renewable fractions used and emergy density. The actual mass, energy, labor and money flows are multiplied by appropriate UEVs in order to bring into the assessment both the biosphere and economic metabolism for resource generation, processing and use. Finally, the social aspects are captured in terms of emergy-based intensity indicators of resource trade, emergy per person and emergy per unit GDP, all related to a country's development and standard of life.

As a consequence, a final sustainability assessment can be drawn through aggregate performance indicators EYR, ELR and ESI (Table 12.7, items 23, 24, and 25).

The EYR (Emergy Yield Ratio) is defined as the ratio of total emergy use to the emergy that is imported from outside. A large EYR value indicates that a national economy largely relies on local resources, by comparing the emergy locally available with the amount that is imported. In the investigated period China shows a declining trend from 1978 to recent years, with fluctuations upward in the years 1990 (a year with decreased trade due to political events in 1989 and increased reliance on local resources) and 2009 (Figure 12.16). It remains to be investigated based on further data if this is an actual reversal trend, perhaps generated by less imports due to the world economic turmoil in 2009.

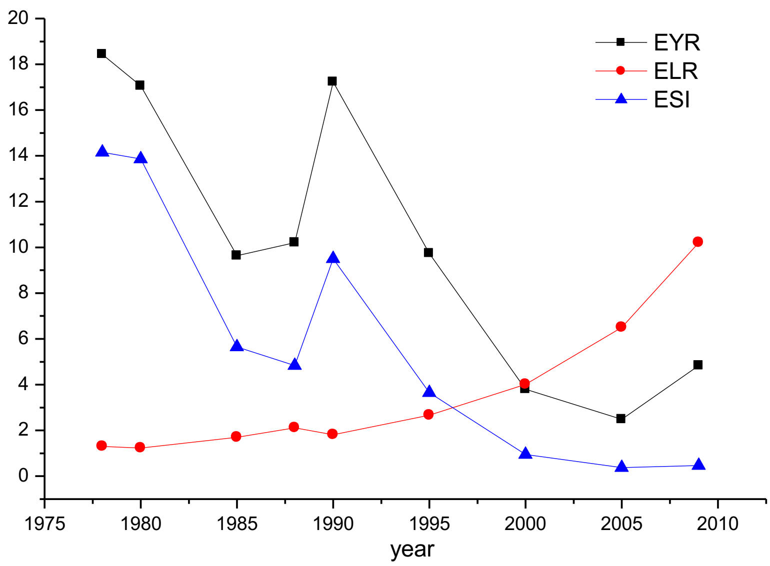



**Figure 12.16. Trends of EYR, ELR and ESI in China.**

The ELR (Environmental Loading Ratio) of China shows a steady increase over time, as consequence of increased local nonrenewable emergy as well as imported emergy resources (Figure 9). It should be clearly stated that a high ELR is not an indicator of a high local pollution in conventional sense. For instance, if a country imports electricity from a nearby country, this electricity flow is likely to help decrease the local pollution at the expenses of the environment in the electricity producing country. Therefore, the ELR should be rather considered as an

indicator of investment pressure on the local environment and locally available resources. When nonrenewable and imported resources are used to develop an economic activity (a farm, an industry, a city), the area where the investment occurs is no longer the untouched ecosystem it was previously (forest, grassland, etc), but becomes a human-dominated system where the locally renewable sources play a minor role. Therefore, the ELR can be considered a measure of distance of the human-dominated development from the fully natural state. A huge distance suggests a smaller sustainability, due to the dependence on nonrenewable and imported sources. To this regard, China has not been performing better in the most recent years (Figure 12.16).
The EYR and the ELR can be linked into an aggregate assessment of economic performance and environmental load, defined as Emergy Sustainability Index (ESI= EYR/ELR), suggesting a global sustainability picture for the system under study. The rationale is that a country should try to rely on local resources to the largest possible extent (in so increasing the EYR) and, at the same time, should try to minimize its environmental load (distance from the natural reference level) by decreasing the use of nonrenewables (Ulgiati and Brown, 1998; Brown and Ulgiati, 2011). These two strategies would make the ESI increase, thus making the country more sustainable (less dependent on outside and less dependent on nonrenewables). Unfortunately, this is not yet the case of China (similar to most developed and developing countries in the world). In fact, Figure 12.16 clearly shows a declining trend of China's ESI, in the investigated period.

*An emergy-based policy for China*

Trends of emergy use, GDP and resource use per capita and environmental performance indicators clearly show that China is pursuing its economic growth on the wrong track, by following the same quantitative growth pattern as western countries did up-to-date. Such pursuit of quantitative growth is now showing its shortcomings in the most developed world economies, not only in western countries, with market and social instability, large resource demand, and unsustainable environmental degradation (Lei and Zhou, 2012).

Brown and Ulgiati (2011) identified quantitative growth as "the first, second, and third commandments of the current economic paradigm that insists that human well being and happiness is linked to increasing income." As an alternative to business-as-usual policies, they suggest "…the future can still be about growth, but according to other parameters and different measures of wealth. Such changes must be accompanied by appropriate policies that recognize new values as the basis for qualitative, not quantitative growth. We cannot achieve sustainability without redefining and redirecting human wants in ways that are less consuming of natural resources." Having realized that Chinese economic growth is coupled to large environmental resource use and that environmental performance indicators show a worsening of the global country's sustainability, it is of paramount importance to identify resource use policies for China based on calculated emergy indicators. As already pointed out, the added value of emergy indicators is that they do not only include energy and monetary flows, but they also take into account other resource flows and storages (minerals, soil, labor) as well as the needed environmental support for resource generation and processing.

Based on our results, three main policies are needed and urgent:

a) Stopping pursuit of quantitative growth, promoting life style innovation.

Following the western countries paradigm of quantitative growth at any cost would quickly consume Chinese natural capital and diminish the ecosystem services presently available, in so affecting the quality of life of Chinese populations and creating conditions of environmental and social instability. What is needed in China is not an unsustainable increased number of cars and roads, built environment, consumer goods designed for landfill, etc, because this involves increased extraction and burning of fossil fuels, increased mining, increased soil erosion, increased movement of sediments from land to oceans, increased deforestation, air and water pollution. Policies must find new patterns where the present needs are satisfied without putting at risk the needs of future generations. For the sake of clarity, a good mix and planning ahead of mass and individual transportation patterns would be able to meet the increasing demand for freight and passenger transport without falling into the failure of car dominance, liquid fuel shortage, air pollution and eventually nightmare mobility that characterizes most if not all world big cities. The strategy should therefore be an offer of services that meet demand (e.g. transportation, health, culture, leisure) instead of an increased offer of products unlikely to meet such demand for a suitable time.

b) Increasing efficiency of resource use (not only energy).

This would allow less use of minerals, metals, fossil fuels and land, all factors that are limiting already and might become even more limiting in the near future. Such strategy would lead to a decreased percentage of nonrenewable resource use, presently around 90% of total emergy use. If nonrenewable uses decline, thanks to innovative lifestyles and increased efficiency, the share of emergy use that is renewable would increase again, from the present negligible 9% back to higher values much closer to the 46% in 1978. Most of Chinese electricity is presently generated out of fossil fuels (mainly coal, about 70%); the share of renewable energy use (not only electricity) has been, in the year 2009, a low 11.8% of total Primary Energy Supply (out of which 2.8% hydro, geothermal, wind, solar; 9% biomass and waste; nuclear not included) (IEA, 2012). This means that there is a possibility to increase renewable energy use at the expenses of nonrenewable resources such as coal and oil. We are not advocating here a decrease of electricity use, since electricity allows the use of more efficient and locally clean devices (electric engines, electric cars, online business), but instead the generation of electricity through renewable and/or cleaner technologies. The same may happen with transportation, where improved technology and integrated transportation modalities may decrease the fossil emergy use (at present 28% of total use) to a significant extent. Since a large fraction of total nonrenewable emergy use is minerals, metals and other non-energy goods, matter flow efficiency is also important, in that it allows decreased mining, decreased environmental disruption, and decreased indirect energy use for mineral processing. Efficiency in matter flow processes must also be coupled to increased recycling of all abiotic and biotic materials, whenever this is possible. Recycling is specially important with rare earth minerals, of which China is the most important producer and exporter and that are among the most strategic chemical species in the electronic and renewable energy industries.

c) Implementing trade equity.

International stability requires fulfillment of basic needs of populations in all world countries. According to Brown and Ulgiati (2011), “we should recognize that when some economies grow, others are impoverished.” We have shown in the Material and Methods Section that equity of trade can only be achieved when emergy flows are balanced, not money flows only. We have also shown that China, at present, sends out more emergy than it receives in trade, thus losing resources although slightly increasing money income associated to exports. Policies for improved Chinese economy and standard of living must be increasingly based on less raw resource exports and more inside processing, which is already gradually happening. In so doing, manufactured goods could be sold at higher price per unit of emergy associated, which would increase domestic jobs and therefore foster more sustainable standards of life.

*Scotland*

The largest local non-renewable (or very slowly renewable) source is coal if only onshore activities are accounted for or oil and natural gas if *extra-regio* activities are taken into the account on either population or area basis. Extraction of igneous rock is also important. The largest import in 2001 is represented by the category of crude materials (except fuels) but in 2010 the importance of imported fuels has increased greatly. The emergy of services sums the emergy of money related to the imported goods to express the total emergy imported by a country through the trade process. Considering only onshore emergy for Scotland, imported services are the largest single component of the emergy mix exceeded only by the combined emergy of waves and tides, which remain largely uncaptured by the economic system with the exception of production from aquaculture, fisheries and all other economic uses of marine renewable emergy. Such a balance is typical of socio-economic systems where a large fraction of total imports are high value–added manufactured goods (e.g. electronics, fashion items etc.) rather than primary resources (e.g. oil or minerals) for subsequent processing. When offshore emergy is included the character of Scotland's emergy mix changes (markedly if a geographical share is applied). In this case the emergy attributed to Scotland is greatly enlarged with the relative importance of all non-offshore emergy components relatively diminished. Yet this dominance of Scotland's emergy by offshore oil and gas has passed its peak. Between 2001 and 2010 the decline in offshore oil and gas in emergy terms has been significant, moving from 41% to 26% of total emergy even using a geographical share.

The histograms in Figure 12.17 can be interpreted as an emergy signature. The columns in Figure 12.17 express the diversity of sources and the magnitudes of the different emergy input resources supporting the metabolism of Scotland. The signature also includes the different allocation alternatives for fossil fuels based on per capita or geographic shares to show how much these accounting or sharing decisions affect the character of Scotland's emergy signature.

The main emergy indicators for Scotland in 2001 and 2010 are shown in Table 12.9. Using the data from this table it is possible to take a range of perspectives, macro-emergy flow extents and intensities, the balance of sources, their renewability and the relative importance of local and global flows. The table is also set up to allow assessment of the importance of emergy included as part of services within Scotland, change over time between 2001 and 2010, and the importance of how the offshore component is assessed.

The **Import/Export** ratio shows a shift from an exporting status to a more fair-trading stance over time. Usually countries in the developed world show a ratio higher than 1 indicating that more emergy is imported than exported for the money paid. This is good for individual countries and can be considered a driving force for international trade. On the other hand, a ratio below 1 suggests that more emergy is exported (wood, fossil fuels, etc.) than imported. If the value calculated for onshore Scotland for the year 2001 (0.76) continued into the future, Scotland would in effect be exporting its wealth potential without appropriate feedback from outside (in emergy or financial terms).

The **Environmental Loading Ratio (ELR)** values calculated here indicate high overall levels of naturalness for Scotland, especially for Scotland onshore which has an ELR value ranging from 2.5 and 2.85 (without Labour and Services) to 3.48 and 3.75 (with Labour and Services) for the years 2001 and 2010 respectively. This is characteristic of a system that is relatively low intensity or that has significant area over which the effects of economic activities can be diluted. Pereira et al. (2013) recently calculated average ELRs for Brazil and Italy as 5.48 and 21.28 respectively (for the year 2008).

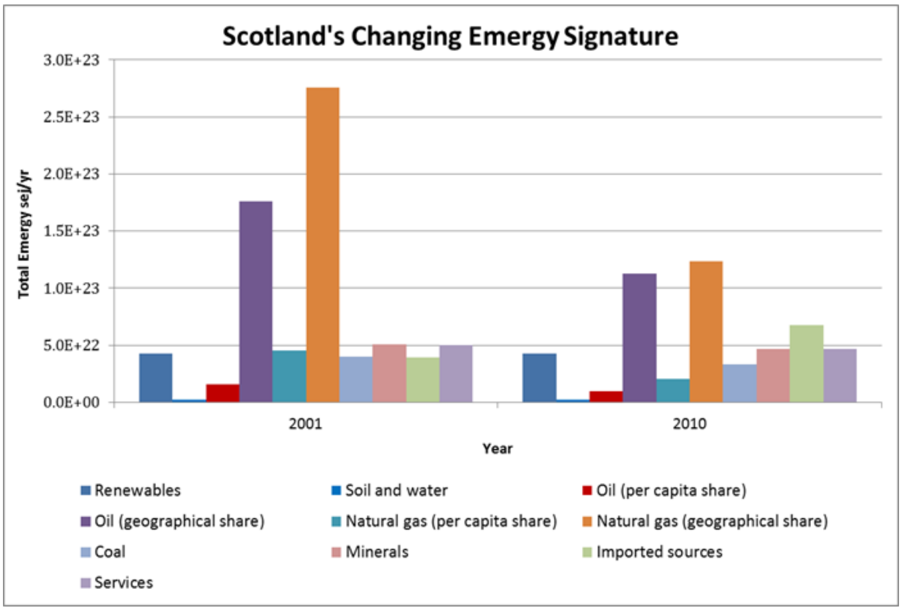


Figure 12.17. The overall emergy signatures of Scotland in 2001 and 2010

Changes in the **Emergy Yield Ratio** (EYR) for Scotland indicate a strong reliance on external emergy sources and that this dependence is increasing. The main source of this increase in imported emergy is fossil energy sources. An EYR value of less than 2.0 indicates a nation that transforms imported resources into products, with minimal local contributions (and Scotland is close to this value when considering the onshore emergy only. While values of close to 1.0 are theoretically possible where no local resources are required, these would tend to be associated with information flows or other digital services and even here there will be draw down on local resources via societal overhead and infrastructure. The contrast, if offshore activities are included is very strong, with EYRs typical of the primary energy sector alone (close to or >5.0 for the geographic shares of *extra-regio* emergy). If the system boundary includes fossil fuel reservoirs, the EYR is calculated as much higher, because of the assumption that oil and minerals are local (N). These offshore emergy dominated EYR values have declined substantially from 2001 but even with only a population share they still profoundly affect the overall character of the system. Both perspectives of the system need to be considered in formulating policy. The trend for decreasing EYR in many countries all around the World (Italy, Spain, Taiwan, Brazil, and Sweden) was firstly noticed by Lomas et al. (2008) and then confirmed by Pereira et al. (2013) as one of the effects of the globalization.

The **Emergy Sustainability Index** (ESI) values of greater than 1.0 are associated with systems that result in net contributors to society without undermining the environmental equilibrium. Values of less than 1.0 are typically associated with consumer processes. Being a compound index, it is affected both by the numerator (EYR, a measure of exploitation of local resources by a system investing emergy from outside) and by the denominator (ELR, a measure of the degree of divergence from the state the system would have reached if only driven by locally renewable emergy). The interpretation of Scotland's ESI is significantly affected by the inclusion or omission of services, contrast ESI values of 0.76 for onshore Scotland in 2001 with services to 1.88 without, highlighting the weight of the indirect work (services) embedded in the inputs. The ESI is lower if the offshore components are included because although more local resources are taken into account the relative importance of renewables is greatly reduced. Lomas et al. (2008) show a clear pattern of decrease in the ESI over time for all countries considered, converging towards values as low as 0.10-0.15. Scotland demonstrates higher sustainability values, but conforms to a decline in ESI over time.

The **Emergy Density** for onshore Scotland in 2001 is 2.37E+12 sej/$m^2$. This value increased between 2001 and 2010 by just over 9% and since area is constant this change can be attributed to population increase and changes in the consumption and production mix in Scotland. When offshore sources are considered then the emergy density is much higher but it declines over time. Note as with other indicators, the increase of emergy density onshore over time and the decline offshore is associated with the passing of peak oil and gas in the North Sea.

The **Emergy Use per person** suggests a measure of the potential standard of living (as represented by availability of resources and goods). Per capita values hide the hierarchy of unequal access to resources, for which a more detailed assessment across space, age and income classes would be needed. These values provide a starting point to understand the temporal evolution of a country as a whole as well as to compare countries from the point of view of their welfare development potential. Per capita emergy intensity for onshore Scotland increased between 2001 and 2010. Further investigations are required to attribute the change between productive and consumptive sectors and to determine the balance between increase in consumption of identical products (e.g. homes heated to higher average temperatures) versus changes in the mix of consumption (e.g. imported food replacing home grown). The potential value of the population and geographical share of offshore values again show a higher value that declines over time.

The **Emergy per unit of GDP** is unique among the density indicators for onshore Scotland, as values declined between 2001 and 2010. This can reflect improvements in the efficiency of Scotland's productive sectors through technology change, but it can also reflect changes in the mix of activities to those that generate more wealth per unit of emergy (e.g. services, particularly financial services rather than primary industry or manufacturing). Given the overall growth in onshore emergy used, (a function of both population growth and per capita emergy use), the decrease in emergy intensity per unit of GDP is most likely due to changes in the mix of activities that outweighs the increased extent of emergy use. This indicator has several limitations inherent in the use of GDP, namely the issues of distribution as seen in the per capita indicator, but also the degree to which GDP accounting reflects wealth/lifestyle that affects the quality of life for citizens.

Visualization of change in multiple indices over time is challenging to communicate. One option is the use of radar diagrams in which the indices are arranged on axes radiating out from a central point. Joining the data point on each axis with lines creates a web structure that defines areas, for example for each year in a time series. For such figures to be easy to interpret they require the data to be transformed such that an increase or decrease always implies the same qualitative change (improvement or decline) and that the relative magnitude of change between indicators also needs to be comparable (otherwise the areas generated become a function of the relative scales of the indicators). Meeting these criteria is arguably best done by presenting time series as normalized changes relative to a baseline (though even here interpretation of the significance of magnitudes of change between indices can be challenging). For the figures presented here, the convention is that larger values should be interpreted as more intensive in terms of resources use and in some cases indicating a greater reliance on external sources of emergy that may make the system less sustainable. To that end EYR is replaced by its inverse 1/EYR before the generation of the normalized values. Figures 12.18 present the changes between 2001 and 2010 for the main emergy indicators (including services) for the onshore, geographic and population shares of offshore emergy.

*The rural subsystem*

EMA highlights the strong contrasts between the three subsystems – remote rural, accessible rural and the rest of Scotland. This takes into account renewable sources (within the region's environment even if not captured), resource and commodity inputs from outside the system, and direct and indirect labour flows. Note that in EMA, renewable flows are strictly dependent on the size of the system (in this case on land area) with remote rural having the largest share of these flows. Even accepting this assumptions the contrast between the three sub systems in emergy terms is striking. For the sake of simplicity, in this section, only the population based share of offshore fossil fuel extraction is considered and only indicators including labour and services are shown.
Figure 12.19 shows how the total emergy supporting Scotland was allocated according to the rural classification. Total emergy slightly decreased from 2001 to 2010 for the rest of Scotland and was quite stable for accessible and rural.

The different components of total emergy for the Rest of Scotland compared to the other two subsystems is further illuminated by considering differences and changes in the emergy compositions of the totals (Figure 12.20).
The Rest subsystem is mainly supported by changing local non-renewable and imported flows while instead the Accessible and Remote subsystems are more characterized by more constant flows particularly of renewable resources. The importance of renewable emergy sources in defining the "natural" character of these regions is apparent. The reduction in non-renewables emergy sources as seen previously is mainly due to the reductions in offshore oil and gas production attributed to the Scottish system on a population share basis. The overall increase in imported emergy is clearest for the Rest subsystem.

Interpretation of the contrast between the regions is enhanced if percentage shares per emergy type are used rather than overall magnitudes (Figure 12.20). The Remote rural subsystem is characterized as having more than 70% of its emergy being local-renewable. By contrast, Accessible rural has 43% and the Rest only 6%. It is important to clarify that the emergy accounting method includes as renewables the entire fraction of renewable resources (sun, rain, etc.) on land, even if these resources are not directly under human control. Yet, even if not directly under human control, these emergy flows drive ecosystem functions and services and the latter have tangible value in terms of the functionality and desirability of such environments to humans for residence, recreation, tourism and other socio-economic activities. Traditional energy accounting methods only include as renewable resources the fraction of hydro and solar energy that is managed by society through capture and conversion devices (power plants). In so doing, traditional energy methods are unable to adequately characterize and differentiate between urban and rural subsystems. Of course, we cannot exclude a priori that a fraction of ecosystem services (renewable emergy) assigned to rural areas also benefits the economic and social wellbeing of urban areas and therefore a different allocation criterion might have been adopted instead of relying on the administrative boundaries referred to above. A different allocation choice would have increased the share of renewables supporting the urban districts even if these renewables are physically present only within the rural area. Lou et al. (2015) provided a tentative calculation of the relation between the emissions by urban sources and the buffer area required for sustainable uptake.

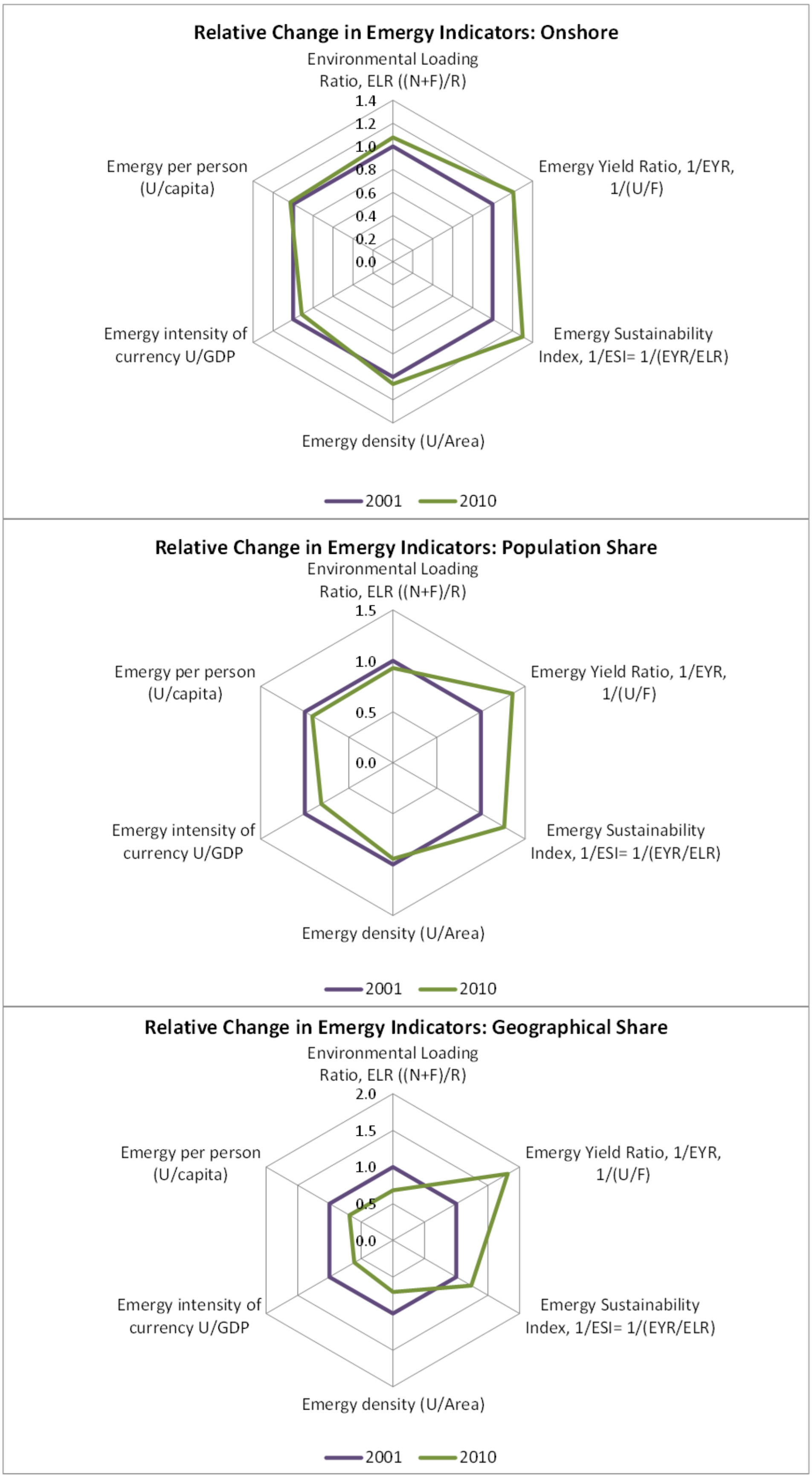


Figure 12.18. Change in main emergy indicators

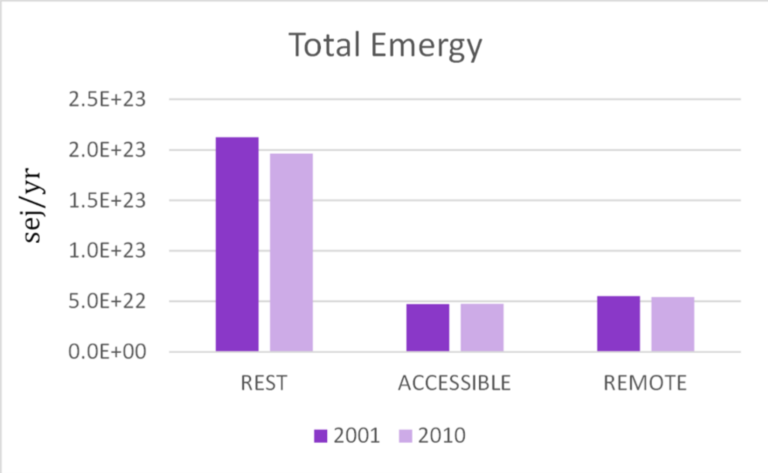


Figure 12.19. Total emergy (sej/yr) supporting the three investigated subsystems

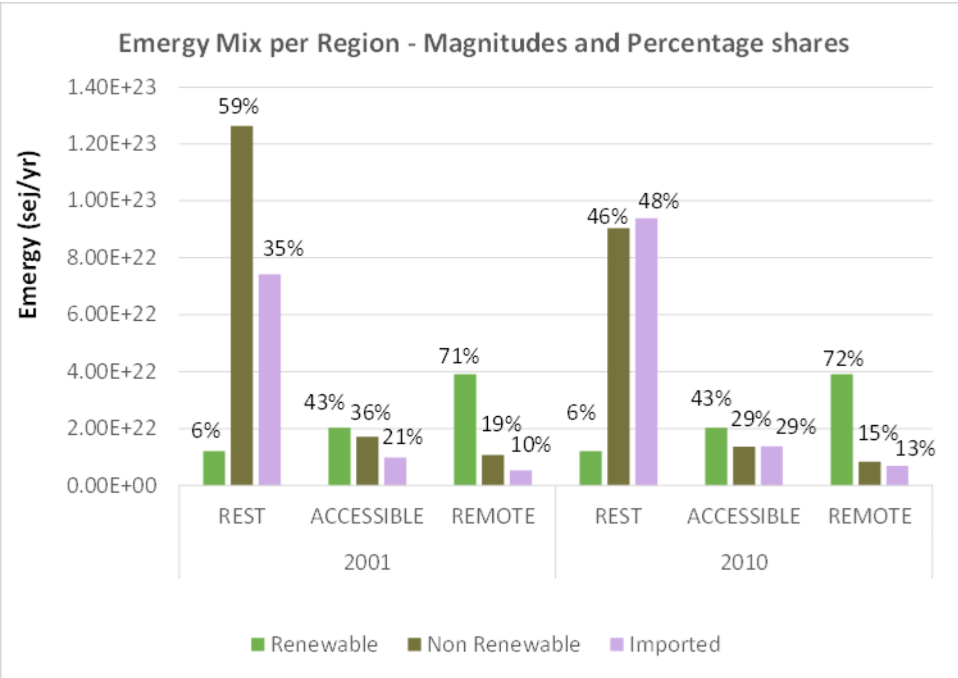


Figure 12.20. Emergy mix for each subsystem in 2001 and 2010

Figure 12.21 shows the main emergy indicators for the year 2010. The non-rural (Rest) region has the highest Environmental Loading Ratio of 15.2, more than three times that estimated for Scotland as a whole. This is due to the concentration of a large share of imported goods and services in more heavily populated environments and the very small renewable share attributed due to the system's limited spatial extent. When the assessment is performed with reference to the administrative area the accessible and remote subsystems show larger shares of renewable emergy to counter act their shares of non-renewable and imported emergy and they thus have lower Environmental Loading Ratios and higher Emergy Yield and Emergy Sustainability indices. If the assessment is performed per person or with reference to a different allocation of renewables as pointed out above results are likely to show a higher fraction of renewables supporting urban population. This overall pattern for accessible and remote rural systems needs to be better characterized in terms of empirically derived and localized rates of non-renewable and imported resources. This is true for both the productive and household sectors, each of which may be hypothesized to have distinctly different rates and mixes of emergy use when compared to their urban equivalents.

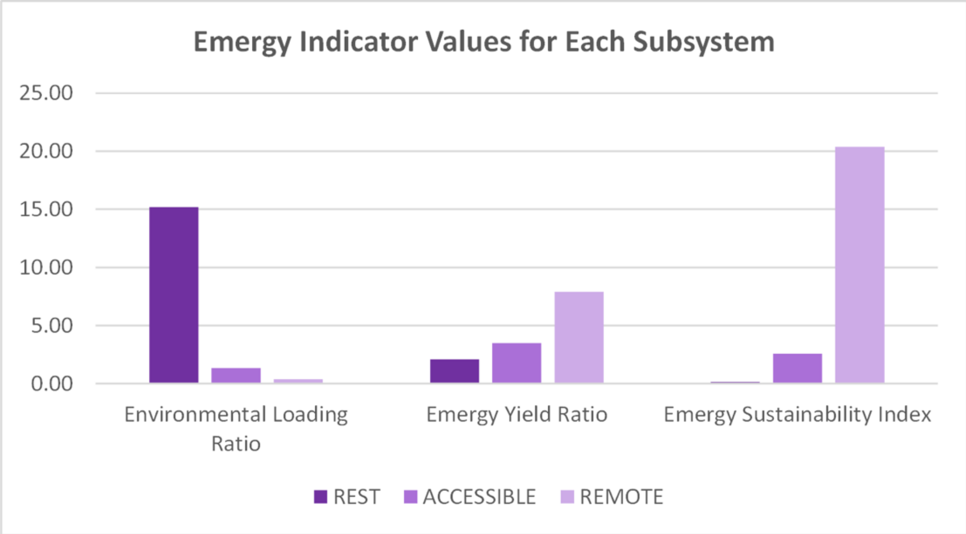



Figure 12.21. Emergy indicator values for each of the subsystems

Finally, Figure 12.22 shows the emergy per unit area, per capita and per unit of GDP, for each of the subsystems, for the year 2010. The areal intensity chart shows the extreme concentration of emergy in space associated with urbanized systems, with 94% of the emergy from non-renewable or imported sources. While emergy is highly concentrated in urban areas, the people living in rural areas inhabit systems that have higher levels of emergy present per capita. Much of this is not captured by human systems or consumed *per se,* but, does contribute to the quality and character of the environment and thereby to the aggregate quality of life of those that experience it.

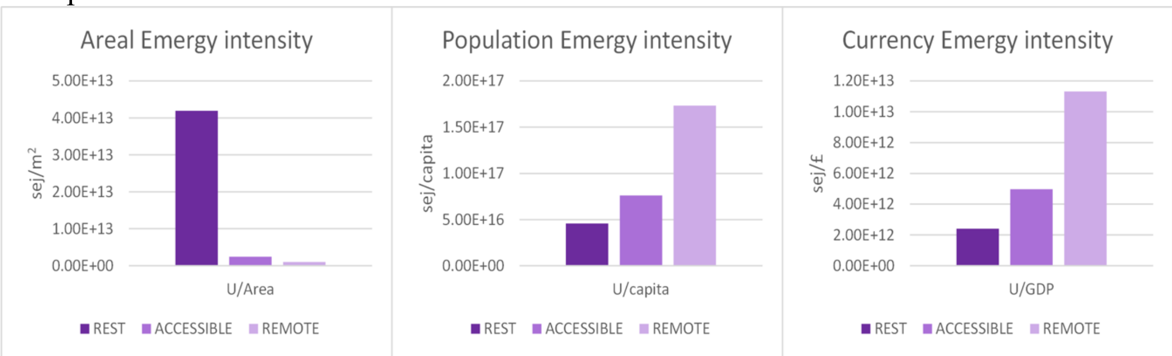



Figure 12.22. Emergy intensity indices for land, per capita and per unit of currency

The emergy intensity of currency per subsystem shows a similar pattern but without a better attribution of the locus of wealth generation and/or expenditure, this index largely reflects the emergy per capita index. Other studies (Cialani et al. 2004; Ferreyra and Brown. 2007; Lomas et al., 2008; Jiang et al., 2008) have shown that emergy per unit of currency is strongly dependent on the sector considered and the sectoral mix present in a region. Terms of trade resulting from power relations within supply chains mean that areas with dependencies on primary industries tend to be relatively disadvantaged (if potentially more sustainable). Yet for rural Scotland (and particularly accessible rural Scotland), it would be unwise to equate the rural economy with land based industries alone. Based on this initial analysis the authors would argue that the emergy characteristics of rural and urban subsystems in Scotland would bear further investigation, in particular the contrasts in sectorial mixes and in the characteristics of their domestic sectors. Work looking at the relationships between rural and non-rural subsystems in terms of flows of wealth, materials, energy and services (both socio-economic and ecosystem) could also be justified.

## ***Conclusions***

National economies and international trade are generally evaluated only in terms of their GDPs and the market value of resources traded. In times of increasing environmental concerns, decreasing resource availability also due to increasing world population and welfare in emerging nations, and finally in times of increasingly globalized economies, the environmental value of resources that support economies and social dynamics cannot be further ignored. Wealth comes from resource availability; resources support the economic process, generate jobs and GDPs, but most of all support lifestyle improvement. Resources used to be traded at low cost between exporting countries and developed buyers. The development of economies in emerging countries as well as the development of international markets is now completely reshaping the way resources are valued and traded. Although geopolitical equilibrium and the power of big corporations and market operators still affect the dynamics of resource uses, it is increasingly clear that market value based on the power of big market players is no longer the only way to assign value to resources. We present in this study an application of the emergy synthesis method to the assessment of the resource basis of selected national economies, Italy, Brazil, China and Scotland, with focus on the major matter and energy sources used, on resource quality, on national economy environmental performance and sustainability, on trade equity. Calculated indicators based on the emergy approach within a life cycle perspective provide a dynamic picture over the evolution of these economic systems and show without any doubt that growth-oriented economic development is strictly linked to decreasing environmental sustainability and trade inequity. Results call for decreased use of nonrenewable resources, increase equity of commercial exchanges, new evaluation methods based on the environmental support to resource generation to complement at the appropriate scale the traditional market values. Emergy-based indicators, complementing conventional energy and matter accounting, have been able to provide a non-conventional perspective of the wealth, trade and environmental performance of these countries and can be applied to every country in Europe and worldwide. It is important to highlight that emergy accounting results presented as time series analysis are definitely strong and appealing, and allow an integration of biophysical indicators with conventional economic indicators such as GDP, income per capita, population growth. The analysis of historical series of emergy flows and indicators was shown in this study to be a very useful and comprehensive tool for the assessment of a country's performance, by bringing into the accounting process important factors such as the environment and the time embodied in resources. Unfortunately, most international databases are still reliant on money flows only. This paper shows that biophysical assessments of economies, capable to develop environmentally comprehensive indicators, are much needed policy tools and should be urgently developed as complements or satellite accounts of international monetary evaluations, implemented by national and international Institutions.

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# APPENDIX

## Calculation procedures (China, 2009)

Footnotes of Table 1

1. SOLAR ENERGY: Cont Shelf Area= 2.71E+10 m2 at 200 m depth (CIA, 2012); Land Area= 9.60E+12 m2 (CIA, 2012); Insolation=1.63E+02 W/m2 (http://swera.unep.net/typo3conf/ext/metadata_tool/archive/browse/256.pdf); Albedo= 0.30 (Dagmar Budikova, 2010); Energy(J)= (area incl shelf)*(avg insolation)*(1-albedo)= (____m2)*(____W/cm2/y)*(1-albedo)*(3.154E7s/yr)= 3.47E+22 J/yr; UEV = 1.00 seJ/J by definition.
2. RAIN, CHEMICAL POTENTIAL ENERGY: Land Area= 9.60E+12 m2 (CIA 2012); Cont Shelf Area= 2.71E+10 m2 at 200 m depth (CIA, 2012); Rainfall= 0.76 m/yr (GE GAO, 2007); Evapotrans rate= 60.0% (GE GAO, 2007); Energy (land) (J)= (area of land)(Evapotransp.rate)(rainfal)(water density)(Gibbs no.)= (____m2)*(____m)*(evapotransp.rate)*(1000kg/m3)*(4.94E3J/kg)= 2.16E+19 J/yr; Energy (shelf) (J)= (area of shelf)(Evapotransp.rate)(rainfal)(water density)(Gibbs no.) = 6.10E+16 J/yr; Total energy (J)= 2.17E+19 J/yr; UEV= 3.05E+04 seJ/J (Odum et al., 2000).
3. RAIN, GEOPOTENTIAL ENERGY: Land Area= 9.60E+12 m2; Rainfall= 0.76 m (GE GAO, 2007); Avg. Elev= 1.47E+03 m (China Statistical Yearbook, 2010); Runoff rate= 40.0% (GE GAO, 2007); Energy(J)= (area)(rainfall)(% runoff)(water density)(average elevation)(gravity)= (____m2)*(____m)*(____%)*(1000kg/m3)*(___m)*(9.8m/s2)= 4.20E+19 J/yr; UEV= 4.70E+04 seJ/J (Odum et al., 2000).
4. WIND ENERGY: Area= 9.60E+12 m2 (CIA 2012); Density of Air= 1.29 kg/m3 (http://hypertextbook.com/facts/2000/RachelChu.shtml); Avg. annual wind velocity= 3.50 mps (http://cdc.cma.gov.cn/atlas/search/win.htm); Geostrophic wind= 5.83 mps (assumed surface winds are 0.6*geostrophic; Reiter, 1969); Drag Coeff.= 0.001 (Miller, 1964; Kraus, 1972); Energy (J)= (area)(air density)(drag coefficient)(velocity$^3$)= (_____m2)(1.3 kg/m3)(1.00 E-3)(______mps)(3.14 E7 s/yr)= 7.72E+19 J/yr; UEV= 2.45E+03 seJ/J (Odum et al., 2000).
5. WAVE ENERGY: Shore length= 1.80E+07 m (China Statistical Yearbook, 2010); Wave height= 0.75 m (http://www.oceanor.no/Services/WWWS); Energy(J)= (shore length)(1/8)(density)(gravity)(wave height2)(velocity)= (__m)(1/8)(1.025E3kg/m3)(9.8 m/sec2)(__m)2(__m/sec)(3.14E7s/yr); Energy(J)= 1.77E+18 J/yr; UEV= 5.10E+04 seJ/J (Odum et al., 2000).
6. TIDAL ENERGY: Cont Shelf Area= 2.71E+10 m2 (CIA, 2012); Avg Tide Range= 1.00 m (Jiang et al., 2008); Density of sea water= 1.03E+03 kg/m3 (http://hypertextbook.com/facts/2002/EdwardLaValley.shtml); Tides/year= 730.00 (estm. of 2 tides/day in 365 days) Energy(J)= (shelf)(0.5)(tides/y)(mean tidal range)2*(density of seawater)(gravity)= (____m2)*(0.5)*(____/yr)*(____m)2*(_____kg/m3)*(9.8m/s2)= 9.94E+16 J/yr; UEV= 7.39E+04 seJ/J (Odum et al., 2000).
7. Surface heat flow: Land Area= 9.60E+12 m2; Heat flow＝63 mW/m×8760(hour/year)x 3600(second/hour)/1000(W/mW)=1.99E+06J/m2; Energy (J)= (area)(Heat flow)= (____m2)(1.00E6 J/m2)= 1.91E+19 J/yr; UEV = 5.80E+04 seJ/J (Odum et al., 2000)
8. FISHERY EXTRACTION: Total 2008 catch:=1.48E+07 ton/yr (FAO, 2010); Sustainable catch estimate= 1.46E+07 ton/yr (Cohen, 2007; FAO, 2005, 2010; UNEP, 2007); Unsustainable extraction estimate: 2.00E+05 ton/yr; UEV= 1.45E+17 seJ/ton.
9. Organic matter in topsoil eroded. Harvested cropland= 1.12E+12 m2 (Chinese Statistical Yearbook, 2010); Soil loss= 4.02E+03 g/m2/yr (Sun, 2011);Total soil loss (g)= 4.50E+15 g/yr. Average organic content (%)= 0.03 %; Organic matter (OM) in soil lost= 1.35E+14 g/yr; Energy of OM (J)= (__g/m2/yr)*( __ m2)*(% organic)*(5.4 Kcal/g)(4186 J/Kcal)= 3.05E+18 J/yr; UEV soil= 1.68E+09 seJ/g (Odum, 1996); UEV of soil O.M.= 7.40E+04 seJ/J (Brown and Bardi, 2001).
10. INDIGENOUS NATURAL GAS. Production= 8.30E+10 m3/yr (USGS, 2009); Energy (J)= (____ m3/yr)(energy content)= (____m3/yr)*(8966 kcal/m3)*(4186 J/kcal)= 3.12E+18 J/yr; UEV= 8.06E+04 seJ/J (Odum, 2000a).
11. INDIGENOUS OIL. Production= 1.37E+09 barrels/yr (USGS, 2009); Energy (J)= (____ barrel/yr)(energy content)= (____ barrel/yr)*(6.1E9 Joules/barrel)= 8.36E+18 J/yr; HHV= 4.29E+07 J/kg; UEV= 9.07E+04 seJ/J (Odum, 2000a).
12. INDIGENOUS COAL. Production= 2.96E+09 MT/yr (USGS, 2009); Energy (J)= (____ MT/yr)(energy content)= (____ MT/yr)*(2.9E+10 J/Mt)= 8.58E+19 J/yr; UEV= 6.72E+04 seJ/J (Odum, 2000a).
13. INDIGENOUS MINERALS (INCLUDING LIMESTONE AND FERTILIZERS).

| Mineral | Units | China production | REFERENCE | UEV (seJ/g) (*) | Emergy (seJ) |
|---|---|---|---|---|---|
| Asbestos | Mt | 3.80E+05 | USGS, 2009 | 2.40E+09 | 9.13E+20 |
| Barite | Mt | 3.00E+05 | USGS, 2009 | 3.16E+09 | 9.48E+20 |
| Bentonite | Mt | 3.40E+06 | USGS, 2009 | 3.16E+09 | 1.07E+22 |
| Boron | Mt | 1.45E+05 | USGS, 2009 | 3.16E+09 | 4.58E+20 |
| Bromine | Mt | 1.40E+05 | USGS, 2009 | 3.16E+09 | 4.42E+20 |
| Diatomite | Mt | 4.40E+05 | USGS, 2009 | 3.16E+09 | 1.39E+21 |

| | | | | | |
|---|---|---|---|---|---|
| Dolomite | Mt | 8.10E+06 | USGS, 2009 | 3.16E+09 | 2.56E+22 |
| Feldspar | Mt | 2.00E+06 | USGS, 2009 | 7.56E+09 | 1.51E+22 |
| Fluorspar | Mt | 3.20E+06 | USGS, 2009 | 3.16E+09 | 1.01E+22 |
| Graphit | Mt | 7.80E+05 | USGS, 2009 | 2.40E+09 | 1.87E+21 |
| Gypsum | Mt | 4.50E+06 | USGS, 2009 | 3.16E+09 | 1.42E+22 |
| Kaolin | Mt | 7.45E+06 | USGS, 2009 | 3.16E+09 | 2.35E+22 |
| Limestone | Mt | 1.85E+08 | USGS, 2009 | 3.16E+09 | 5.84E+23 |
| Salt | Mt | 6.66E+07 | CHINA STATISTICAL YEARBOOK, 2010 | 3.16E+09 | 2.10E+23 |
| Strontium carbonate | Mt | 3.36E+05 | USGS, 2009 | 3.16E+09 | 1.06E+21 |
| Sulfur | Mt | 9.37E+06 | USGS, 2009 | 3.16E+09 | 2.96E+22 |
| Talc and related materials | Mt | 2.30E+03 | USGS, 2009 | 2.40E+09 | 5.53E+18 |
| Nitrogen | Mt | 4.23E+07 | CHINA STATISTICAL YEARBOOK, 2010 | 3.16E+09 | 1.34E+23 |
| Phosphate | Mt | 1.80E+07 | USGS, 2009 | 3.16E+09 | 5.69E+22 |
| Potash | Mt | 3.00E+06 | USGS, 2009 | 3.16E+09 | 9.48E+21 |
| **Total** | **Mt** | **3.47E+08** | | | **1.10E+24** |
| **Average UEV of minerals (seJ/g)** | | | | **3.18E+09** | |
| **(*) Source for UEVs: Odum (1996), updated** | | | | | |

14. INDIGENOUS METALS (USGS, 2009)

| Metal | Units | China production | UEV (seJ/g) | Emergy (seJ) |
|---|---|---|---|---|
| Iron | Mt | 6.25E+08 | 1.20E+10 | 7.50E+24 |
| Lead | Mt | 1.60E+06 | 4.80E+11 | 7.68E+23 |
| Lithium | Mt | 7.42E+02 | 9.27E+11 | 6.87E+20 |
| Magnesium (and alloy) | Mt | 5.01E+05 | 6.14E+09 | 3.08E+21 |
| Manganese | Mt | 2.40E+06 | 3.50E+11 | 8.40E+23 |
| Mercury | Mt | 1.40E+03 | 4.20E+13 | 5.88E+22 |
| Molybdenum | Mt | 9.35E+04 | 7.00E+11 | 6.55E+22 |
| Nickel | Mt | 8.10E+04 | 2.00E+11 | 1.62E+22 |
| Rare Earth Metals | Mt | 1.29E+05 | 1.40E+10 | 1.81E+21 |
| Silicon | Mt | 9.50E+05 | 1.80E+09 | 1.71E+21 |
| Silver | Mt | 2.90E+03 | 4.50E+11 | 1.31E+21 |
| Tin | Mt | 1.15E+05 | 1.70E+12 | 1.96E+23 |
| Titanium | Mt | 3.30E+05 | 6.42E+10 | 2.12E+22 |
| Tungsten | Mt | 5.10E+04 | 1.07E+12 | 5.46E+22 |
| Vanadium | Mt | 2.19E+04 | 7.22E+10 | 1.58E+21 |
| Zinc | Mt | 3.40E+06 | 7.20E+10 | 2.45E+23 |
| **Total 2009** | | **6.34E+08** | | **1.25E+25** |
| **Average UEV of metals (seJ/g)** | | | 1.96E+10 | |

15. IMPORTED NATURAL GAS. Nat. gas mass= 7.46E+09 m3/yr (CHINA STATISTICAL YEARBOOK, 2010); Energy (J)= (____ m3/yr)*(8966 kcal/m3)*(4186 J/kcal)= 2.80E+17 J/yr; UEV of natural gas= 8.06E+04 seJ/J (Odum, 2000a).
16. IMPORTED OIL. Oil and oil derived fuels mass= 2.76E+11 L/yr (CIA 2009); Energy (J)= (____ L/yr)*(1.14E4kcal/L)*(4186 J/kcal)= 1.32E+19 J/yr. UEV of imported oil and refined oil products= 1.11E+05 seJ/J (Odum, 2000a).

17. IMPORTED COAL. Coal mass= 4.03E+07 MT/yr(NEAD 2011); Energy (J)= (_ MT/yr)*(2.9E10 J/Mt)= 1.17E+18 J/yr; UEV of coal= 6.72E+04 seJ/J (Odum, 2000a).
18. IMPORTED METALS: Non-ferrous metals= 2.40E+07 MT/yr (data refer to year 2008) (NEAD 2011); UEV non ferrous metals= 3.17E+10 seJ/g (average UEV from NEAD 2011 data). Ferrous metals= 1.34E+07 MT/yr (data refer to year 2008) (NEAD 2011); UEV ferrous metals= 1.17E+10 seJ/g (average UEV from NEAD 2011 data). Total Imports = 3.74E+07 MT/yr= 3.74E+13 g/yr; UEV= 2.46E+10 seJ/g (weighted from average UEVs from NEAD 2011 data).
19. IMPORTED MINERALS. Imports mass= 5.36E+07 MT/yr (data refer to year 2008) (NEAD, 2011)= 5.36E+13 g/yr; UEV= 3.29E+09 seJ/g (average UEV from NEAD 2011 data).
20. IMPORTED FOOD AND AGRICULTURAL PRODUCTS. Mass of imports= 5.43E+07 MT/yr (NEAD, 2011); UEV= 1.13E+10 seJ/g (average UEV from NEAD 2011 data).
21. IMPORTED CHEMICALS, PLASTICS AND RUBBER. Mass of imports= 1.00E+08 MT/yr (NEAD, 2011)= 1.00E+14 g/yr; UEV= 5.90E+09 seJ/g (average UEV from NEAD 2011 data).
22. IMPORTED INDUSTRIAL &TRANSPORTATION MACHINERY. Mass of imports= 8.83E+06 MT/yr (NEAD, 2011)= 8.83E+12 g/yr; UEV= 2.22E+10 seJ/g (average UEV from NEAD 2011 data).
23. SERVICES ASSOCIATED TO IMPORTS. Money paid for imports= 1.01E+12 US $ (data refer to year 2009, WTO, 2010); World Emergy/GWP ratio= 2.00E+12 seJ/$ (Brown and Ulgiati, 2011).
24. EXPORTED FOOD and AGRICULTURAL PRODUCTS. Mass of exports= 7.38E+11 kg/yr (NEAD 2011); UEV= 4.09E+08 seJ/g (average UEV from NEAD 2011 data).
25. EXPORTED ORES AND MINERALS. Mass of exports= 3.03E+07 MT/yr (NEAD 2011)= 3.03E+13 g/yr; UEV= 4.36E+09 seJ/g (average UEV from NEAD 2011 data).
26. EXPORTED FUELS. Mass of exports= 6.06E+07 MT/yr(NEAD 2011)= 6.06E+13 g/yr; UEV= 1.78E+09 seJ/g (weighted average UEV from NEAD 2011 data).
27. EXPORTED METALS. Mass of non-ferrous metals= 3.90E+07 MT/yr (data refer to year 2008) (NEAD 2011); UEV non ferrous metals= 1.77E+10 seJ/g (average UEV from NEAD 2011 data). Mass of ferrous metals= 6.02E+07 MT/yr (data refer to year 2008) (NEAD 2011); UEV ferrous= 1.43E+10 seJ/g (average UEV from NEAD 2011 data). Total mass of exports= 9.92E+07 MT/yr= 9.92E+13 g/yr; UEV of exported metals= 1.56E+10 seJ/g (weighted average UEVs from NEAD 2011 data).
28. EXPORTED CHEMICALS. Mass of exported chemicals= 2.21E+07 MT/yr (data refer to year 2008; after NEAD, 2011)= 2.21E+13 g/yr; UEV= 1.01E+10 seJ/g (average UEV from NEAD 2011 data).
29. EXPORTED INDUSTRIAL AND TRANSPORTATION MACHINERY. Mass of exports= 5.70E+07 MT/yr (data refer to year 2008, after NEAD, 2011)= 5.70E+13 g/yr; UEV= 2.08E+10 seJ/g (weighted average UEV from NEAD 2011 data).
31. SERVICES ASSOCIATED TO EXPORTS. Money received for exports= 1.20E+12 US $ (data refer to year 2009; WTO, 2010). Country's Emergy/GDP ratio= 8.57E+11 seJ/Yuan RMB (This study).

## Calculation procedures for Italy and Brazil

**Unit Emergy Values calculated in this study:**

**UEV OF CHEMICAL POTENTIAL ENERGY OF RAIN**

Rain: global annual average precipitation= 2.6 mm/day (Adler *et al.*, 2003)

Earth surface (land and sea)= 5.10E+08 km2

Energy= 2.6 (mm/day) * 0.001 (m/mm) * 365 (days/yr) * 5.10E+08 (km2) * 1.00E+06 (m2/km2) * 1.00E+06 (g/m3) * 4.94 (J/g)= 23.90E+20 J/yr

UEV of chemical potential energy of rain= global solar emergy / energy flow= 15.83E+24 (seJ/yr) / 23.9E+20 (J/yr)= 6610 seJ/J (Brown and Ulgiati, in press, calculated 6360 seJ/J based on the new baseline 15.2E+24 seJ/yr)

**UEV OF CHEMICAL POTENTIAL ENERGY OF RIVER FLOW**

Total rain on land= 2.1 (mm/day) *1.00E-03 (m/mm) * 365 (days/yr) * 1.48E+14 (m2) *1000 (kg/m3)= 1.14E17 kg/yr

Emergy driving Chemical potential energy dissipation= 1.14E+20 (g/yr) * 4.94 (J/g) * 6610 (seJ/J)= 3.72 E24 seJ/yr

Global annual stream discharge (runoff originating rivers) = 3.99E+04 km3/yr of water (Dai *et al.,* 2009)

Chemical Energy of Runoff water= 3.99E+19 (cm3/yr) * 1.00E+00 (g/cm3) * 4.92 (J/g) = 1.96E+20 J/yr

UEV of chemical potential energy of river flow= 3.72E+24 (seJ/yr) / 1.96E+20 (J/yr)= 19000 seJ/J

**UEV OF GEOPOTENTIAL ENERGY OF RAIN**

Land surface is 29% of the Earth surface= 5.10E+08 (km2) * 29%= 1.48E+08 km2= 1.48E+14 m2.

Total solar emergy referred to the land surface (assuming proportionality according to surface area)= 15.83E+24 (seJ/yr) * 29%= 4.59E+24 seJ/yr (emergy driving geopotential rain on land)

Rainfall on land= 2.1 (mm/day) (Adler *et al.*, 2003)

Total rain on land= 2.1 (mm/day) * 1.00E-03 (m/mm) * 365 (days/yr) * 1.48E+14 (m2) * 1000 (kg/m3)= 1.14E+17 kg/yr

Global annual stream discharge= 35% of precipitation on land = 3.97E+16 kg/yr (Dai *et al.*, 2009)

Average elevation of continents= 840 m (Sverdrup *et al.*, 1942)

Gravitational energy dissipated= mgh= 3.97E+16 (kg/yr) * 9.8 (m/s2) * 840 (m)= 3.27E+20 J/yr

UEV of geopotential energy of rain= 4.59E+24 (seJ/yr) / 3.27E+20 (J/yr)= 14000 seJ/J

## Brazil, 2008:

**RENEWABLE LOCAL SOURCES**

**1. Solar radiation.** land area= 8.50E+12 m2 (CIA, 2008); continental shelf area= 7.10E+11 m2 (CIA, 2008); radiation= 130.8 W/m2 (average 1983-1991); energy= total area (m2) * radiation (W/m2) * 3.15E+07 (s/yr)= 3.80E+22 J/yr; UEV= 1 seJ/J (Odum, 1996); emergy= 3.80E+22 seJ/yr

**2. Deep heat.** land area= 8.50E+12 m2 (CIA, 2008); heat flow= 1.87E+06 J/m2 (Sclater *et al.,* 1980); energy= area (m2) * heat flow (J/m2)= 1.59E+19 J/yr; UEV= 5.80E+04 seJ/J (Odum, 2000); emergy= 9.22E+23 seJ/yr

**3. Tide.** continental shelf area= 7.10E+11 m2 (CIA, 2008); average tide range= 2.98 m (Brown and Cohen, 2006); number of tides= 1.86 #/day (Brown and Cohen, 2006); seawater density= 1025 kg/m3; energy= continental shelf (m2) * 0.5 (half of tidal energy is supposed to be absorbed at the shelf) * #tides/yr * height^2 (m2) * 1025 (kg/m3) * 9.8 (m/s2)= 1.10E+19 J/yr; UEV= 7.40E+04 seJ/J (Odum *et al.,* 2000); emergy= 8.14E+23 seJ/yr

**4. Wind.** superficial average speed= 2.00E+00 m/s (New *et al*., 1999); geostrophic average speed= 3.30E+00 m/s (assuming superficial wind 0.6 * geostrophic); air density= 1.23 kg/m3 (Odum, 1996); drag coefficient= 0,001; energy= total area (m2) * 1.23 (kg/m3) * 0.001 * geostrophic speed^3 (m3/s3) * 3.15E+07 (s/yr)= 1.20E+19 J/yr; UEV= 2.50E+03 seJ/J (Odum *et al*., 2000); emergy= 3.00E+22 seJ/yr

**5. Rainfall and river.** continental shelf area= 7.10E+11 m2 (CIA, 2008); land area= 8.50E+12 m2 (CIA, 2008); total Amazon river basin area= 6.11E+12 m2 (63 % inside Brazil; 37% outside watershed contributing to the Amazon river) (ANA, 2012); watershed outside Brazil= 6.11E+12 (m2) * 37 %= 2.26E+12 m2; watershed inside Brazil= 6.11E+12 (m2) * 63 %= 3.85E+12 m2; rainfall= 2.04 m/yr (Braga *et al*., 1998); volume of rainfall from other countries= 2.26E+12 (m2) * 2.04 (m/yr)= 4.61E+12 m3/yr; volume of rainfall within Brazil= 3.85E+12 (m2) * 2.04 (m)= 7.85E+12 m3; evapotranspired water= 1.22 m (Braga *et al.,* 1998); evapotranspired water / rainfall= 1.22 (m) / 2.04 (m)= 60 % (assuming that the runoff is 40 % and becomes inflowing rivers); average regional altitude variation estimated= 500 m.

**Geopotential**

**Geopotential energy of rivers from other countries contributing by inflowing Amazon river**= volume of rainfall from other countries (m3/yr) * runoff (40 %) * 1.00E+03 (kg/m3) * 9.8 (m/s2) * 500 (m)= 9.04E+18 J/yr; UEV= 14000 seJ/J; emergy= 1.27E23 seJ/yr

**Geopotential energy of inside runoff contributing by inflowing Amazon river**= volume of rainfall within Brazil (m3/yr) * runoff (40 %) * 1.00E+03 (kg/m3 * 9.8 (m/s2) * 500 (m)= 1.54E19 J/yr; UEV= 14000 seJ/J; emergy= 2.15E+23 seJ/yr.

**Total geopotential emergy (outside rivers + inside runoff)**= 1.27E+23 (seJ/yr) + 2.15E+23 (seJ/yr)= 3.42E+23 seJ/yr

**Chemical potential**

**Rain's chemical potential**. energy on land= land area (m2) * rainfall (m/yr) * 1.00E+06 (g/m3) * 4.94 (J/g)= 8.57E+19 J/yr; energy on shelf= shelf area (m2) * rainfall (m/yr) * 1.00E+06 (g/m3) * 4.94 (J/g)= 7.15E+18 J/yr; total energy= 9.28E+19 J/yr; UEV= 6610 seJ/J (this work, according to Brown and Ulgiati, in press); emergy= 6.13E+23 seJ/yr

**Inflowing river's chemical potential**. energy= runoff (40 %) * volume of rainfall from other countries (m3/yr) * 1.00E+06 (g/m3) * 4.94 (J/g) = 9.11E+18 (J/yr); UEV= 19000 seJ/J; emergy= 1.73E+23 seJ/yr

**Total chemical potential emergy (outside rivers + inside rain)**= 6.13E23 (seJ/yr) + 1.73E+23 (seJ/yr)= 7.86E+23 seJ/yr

**6. Waves.** coastal length= 7.50E+06 m (CIA, 2008); average wave height= 1.35 m (Odum, 1996); wave average speed= SQR (9.8 (m/s2) * depth (2m))= 4.4 m/s; waves= coastal length (m) * 1/8 * 1025 (kg/m3) * 9.8 (m/s2) * height^2 (m2) * speed (m/s) * 3.15E+07 (s/yr)= 2.42E+18 J/yr; UEV= 5.10E+04 seJ/J (Odum, 1996); emergy= 1.23E+23 seJ/yr

**7. Marine currents.** 1 sV (Sverdrup)= 1.00E+06 m3/s; Brazilian current= 5.00 sV 20°S (Peterson and Stramma, 1990; Stramma et al., 1990)= 1.60E+14 m3/yr; 18.00 sV 33°S (Olson et al., 1988; Peterson and Stramma, 1990)= 5.76E+14 m3/yr; 20.00 sV 38°S (Olson et al. 1988; Peterson and Stramma 1990)= 6.40E+14 m3/yr; average flow= 4.59E+14 m3/yr; average mass= 4.59E+17 kg/yr; average speed= 4.00E-01 m/s (Calil et al., 2008); kinetics energy= (average mass * average speed^2)/2= 3.67E+16 J/yr; UEV= 1.87E+07 seJ/J (Odum, 2000 – ocean circulation); kinetics energy emergy= 6.86E+23 seJ/yr; nutrients concentration= 3.00E-07 g/L (Metzler et al., 1997)= 3.00E-10 g/m3; volume= 4.59E+14 m3/yr; nutrients= 1.38E+05 g/yr; nutrients energy= 2.30E+09 J/yr; UEV= 1.31E+05 seJ/J (Odum and Arding, 1991); emergy= 3.02E+14 J/yr; total currents emergy= 6.86E+23 seJ/yr

**Renewable flow=** 7.86E+23 seJ/yr (biggest renewable: chemical potential of rainfall and rivers)

**NON-RENEWABLE LOCAL SOURCES**

**8. Forest extraction**. average land use change= 2.30E+06 ha/yr (GRID-GENEVA GEO-3 forest loss); biomass density= 2.10E+02 ton/ha (Penman et al., 2003); forest non-renewable use= biomass density (ton/ha) * land use change (ha)= 4.83E+08 ton/yr; energy= forest use (ton/yr) * 1.80E+10 (J/ton)= 4.14E+18 J/yr; UEV= 5.86E+04 seJ/J (Odum, 1996 (wood biomass)); emergy= 2.43E+23 seJ/yr

**9. Fishery**. fish loss= 6,10E+10 g/yr (FAO, 2005); UEV= 2.78E+11 seJ/g (Odum, 1996); emergy= 1.70E+22 seJ/yr

**10. Water non-renewable extraction**. water non-renewable extraction= 0.00E+00 m3/yr (FAO, 2010)

**11. Soil loss: organic matter**. permanent culture= 1.70E+07 g/ha/yr (Projeto ECOAGRI, 2006: annual culture 17 ton/ha/yr; temporary culture= 9.84E+06 g/ha/yr (Projeto ECOAGRI, 2006: temporary culture (cane: 9.84 ton/ha/yr)); pasture= 1.00E+07 g/ha/yr (Projeto ECOAGRI, 2006: 10 ton/ha/yr); permanent culture= 1.08E+07 ha (IBGE SIDRA, 2006); temporary culture= 3.68E+07 ha (IBGE SIDRA, 2006); pasture= 1.51E+08 ha (IBGE SIDRA, 2006); permanent culture= 1.84E+14 g/yr; temporary culture= 3.62E+14 g/yr; pasture= 1.51E+15 g/yr; soil's organic matter= 5%; organic matter permanent culture= 9.18E+12 g/yr; organic matter temporary culture= 1.81E+13 g/yr; organic matter pasture= 7.53E+13 g/yr; organic matter energy content= 5.4 kcal/g; total energy= total organic matter (g/yr) * energy content (kcal/g) * 4186 (J/kcal)= 2.32E+18 J/yr; UEV= 1.24E+05 seJ/J (Bargigli and Ulgiati, 2003); emergy= 2.88E+23 seJ/yr

**12. Coal**. coal= 2.49E+06 toe/yr (MME, 2010); energy= coal (toe/yr) * 4.19E+10 J/toe (IEA, 2011)= 1.04E+17 J/yr; UEV= 6.71E+04 seJ/J (Brown and Ulgiati, 2004); emergy= 7.00E+21 seJ/yr

**13. Natural gas.** Natural gas= 2.14E+07 toe/yr (MME, 2010); energy= natural gas (toe/yr) * 4.19E+10 J/toe (IEA, 2011)= 8.96E+17 J/yr; UEV= 8.05E+04 seJ/J (Brown and Ulgiati, 2004); emergy= 7.21E+22 seJ/yr

**14. Oil**. oil= 9.40E+07 toe/yr (MME, 2010); energy= oil (toe/yr) * 4.19E+10 J/toe (IEA, 2011)= 3.94E+18 J/yr; UEV= 9.06E+04 seJ/J (Brown and Ulgiati, 2004); emergy= 3.57E+23 seJ/yr

**15. Minerals**

**iron ore**= 3.51E+14 g/yr (IBRAM, 2010); UEV= 2.22E+09 seJ/g (Buranakarn, 1998); emergy= 7.79E+23 seJ/yr
**gold**= 5.40E+07 g/yr (IBRAM, 2010); UEV= 7.39E+14 seJ/g (Brown and Arding, 1991); emergy= 3.99E+22 seJ/yr
**Total emergy**= 9.16E+23 seJ/yr

**16. Metals**

**ferroalloys**= 9.84E+14 g/yr (MME, 2010); UEV= 4.25E+06 seJ/g (Odum et al., 2000 (iron and steel products); emergy= 4.18E+21 seJ/yr
**pig iron**= 3.49E+13 g/yr (MME, 2010); UEV= 5.43E+09 seJ/g (Bargigli and Ulgiati, 2003); emergy= 1.90E+23 seJ/yr
**aluminum**= 1.66E+12 g/yr (MME, 2010); UEV= 7.76E+08 seJ/g (Odum et al., 2000); emergy= 1.29E+21 seJ/yr
**copper**= 3.84E+11 g/yr (MME, 2010); UEV= 3.36E+09 seJ/g (Brown and Ulgiati, 2004); emergy= 1.29E+21 seJ/yr
**zinc**= 2.49E+05 g/yr (MME, 2010); UEV= 1.14E+11 seJ/g (Odum et al., 2000); emergy= 2.84E+16 seJ/yr
**Total emergy**= 1.96E+23 seJ/yr

**IMPORTS**

**17. Fuels**

**oil**= 1.50E+08 toe/yr (MME, 2010); energy= oil (toe/yr) * 4.19E+10 J/toe (IEA, 2011)= 6.28E+18 J/yr; UEV= 9.06E+04 seJ/J (Brown and Ulgiati, 2004); emergy= 5.69E+23 seJ/yr
**oil co-products**= 1.57E+07 toe/yr (MME, 2010); energy= oil co-products (toe/yr) * 4.19E+10 J/toe (IEA, 2011)= 6.57E+17 J/yr; UEV= 1.11E+05 seJ/J (Odum et al., 2000); emergy= 7.30E+22 seJ/yr
**coal**= 1.30E+07 toe/yr (MME, 2010); energy= coal (toe/yr) * 4.19E+10 J/toe (IEA, 2011)= 5.44E+17 J/yr; UEV= 6.71E+04 seJ/J (Brown and Ulgiati, 2004); emergy= 3.65E+22 seJ/yr
**natural gas**= 9.99E+06 toe/yr (MME, 2010); energy= natural gas (toe/yr) * 4.19E+10 J/toe (IEA, 2011)= 4.18E+17 J/yr; UEV= 8.05E+04 seJ/J (Brown and Ulgiati, 2004); emergy= 3.37E+22 seJ/yr
**Total emergy**= 7.12E+23 seJ/yr

**18. Metals**

**ferroalloys**= 9.09E+10 g/yr (MME, 2010); UEV= 4.25E+06 seJ/g (Odum et al., 2000 (iron and steel products)); emergy= 3.86E+17 seJ/yr
**pig iron**= 0.00E+00 g/yr (MME, 2010)
**aluminum**= 2.12E+11 g/yr (MME, 2010); UEV= 7.76E+08 seJ/g (Odum et al., 2000); emergy= 1.65E+20 seJ/y
**copper**= 3.15E+11 g/yr (MME, 2010) UEV= 3.36E+09 seJ/g (Brown and Ulgiati, 2004); emergy= 1.06E+21 seJ/yr
**zinc**= 4.06E+10 g/yr (MME, 2010); UEV= 1.14E+11 seJ/g (Odum et al., 2000); emergy= 4.63E+21 seJ/yr
**Total emergy**= 5.85E+21 seJ/yr

**19. Minerals**. minerals= 9.40E+13 g/yr (UN COMTRADE, 2010); UEV= 2.22E+09 seJ/g (Buranakarn, 1998); emergy= 2.09E+23 seJ/yr

**20. Agriculture**

**cotton**= 9.94E+10 g/yr (FAO, 2008); UEV= 2.10E+10 seJ/g (Brandt-Williams, 2002); emergy= 2.09E+21 seJ/yr
**rice**= 7.21E+11 g/yr (FAO, 2008); UEV= 1.40E+09 seJ/g (Brown and Ulgiati, 2004); emergy= 1.01E+21 seJ/yr **oat**= 5.20E+08 g/yr (FAO, 2008); UEV= 4.40E+09 seJ/g (Brandt-Williams, 2002); emergy= 2.29E+18 seJ/yr
**potato**= 7.00E+09 g/yr (FAO, 2008); UEV= 2.80E+09 seJ/g (Brandt-Williams, 2002); emergy= 1.96E+19 seJ/yr
**coffee=** 2.28E+08 g/yr (FAO, 2008); energy= coffee (g/yr) * 4.19 (kcal/g) (TACO, 2006) * 80% dry * 4186 (J/kcal)= 3.20E+12 J/yr; UEV= 1.54E+06 seJ/J (Odum et al., 2000); emergy= 4.93E+18 seJ/yr
**orange**= 1.94E+09 g/yr (FAO, 2008); UEV= 1.92E+09 seJ/g (Brandt-Williams, 2002); emergy= 3.72E+18 seJ/yr
**cassava**= 1.88E+10 g/yr (FAO, 2008); UEV= 1.62E+08 seJ/g (Rodrigues et al., 2003); emergy= 3.05E+18 seJ/yr
**corn**= 1.10E+12 g/yr (FAO, 2000); UEV= 7.98E+04 seJ/g (Odum et al., 2000); emergy= 8.78E+16 seJ/yr
**soybean**= 2.56E+10 g/yr (FAO, 2008); UEV= 9.87E+09 seJ/g (Brandt-Williams, 2002); emergy= 2.53E+20 seJ/yr
**wheat**= 6.64E+12 g/yr (FAO, 2008); energy= wheat (g/yr) * 3.60 (kcal/g) (TACO, 2006) * 80% dry * 4186 (J/kcal)= 8.00E+16 J/yr; UEV= 2.67E+05 seJ/J (Odum et al., 2000); emergy= 2.14E+22 seJ/yr
**Total emergy**= 2.48E+22 seJ/yr

**21. Animal products**

**meat=** 1.02E+12 g/yr (FAO, 2008); UEV= 4.85E+10 seJ/g (Brandt-Williams, 2002); emergy= 4.96E+22 seJ/yr
**milk**= 5.10E+11 g/yr (FAO, 2008); UEV= 3.37E+10 seJ/g (Brandt-Williams, 2002); emergy= 1.72E+22 seJ/yr
**eggs**= 2.85E+09 g/yr (FAO, 2008); UEV= 1.07E+11 seJ/g (Brandt-Williams, 2002); emergy= 3.05E+20 seJ/yr
**Total emergy**= 6.71E+22 seJ/yr

**22. Fishery products**. fish= 2.10E+11 g/yr (IBAMA, 2007); UEV= 2.78E+11 seJ/g (Odum, 1996); emergy= 5.84E+22 seJ/yr

**23. Plastics**. plastics= 1.01E+11 g/yr (UN COMTRADE, 2010); UEV= 5.29E+09 seJ/g (Buranakarn, 1998); emergy= 5.34E+20 seJ/yr

**24. Chemicals**. chemicals= 1.40E+13 g/yr (UN COMTRADE, 2010); UEV= 6.38E+09 seJ/g (Odum, 1996 (fertilizer N)); emergy= 8.93E+22 seJ/yr

**25. Machinery and transport.** machinery, vehicles, bicycles, ships= 6.52E+11 g/yr (UN COMTRADE, 2010); UEV= 1.10E+10 seJ/g (Odum et al., 1987b); emergy= 7.17E+21 seJ/yr

**26. Refined goods.** glass, refined metals, wires, textile= 8.55E+11 g/yr (UN COMTRADE, 2010); UEV= 2.69E+09 seJ/g (Buranakarn, 1998 (glass)); emergy= 2.30E+21 seJ/yr

**27. Electricity**. electricity= 3.60E+06 toe/yr (MME, 2010); electricity= (toe/yr) * 4.19E+10 J/toe (IEA, 2011)= 1.51E+17 J/yr; UEV= 3.36E+05 seJ/J (Odum et al., 2000); emergy= 5.06E+22 seJ/yr

**EXPORTS**

**Fuels**

**oil**= 2.24E+07 toe/yr (MME, 2010); energy= oil (toe/yr) * 4.19E+10 (J/toe) (IEA, 2011)= 9.38E+17 J/yr; UEV= 9.06E+04 seJ/J (Brown and Ulgiati, 2004); emergy= 8.50E+22 seJ/yr

**oil co-products**= 1.42E+07 toe/yr (MME, 2010); energy= oil co-products (toe/yr) * 4.19E+10 (J/toe) (IEA, 2011)= 5.95E+17 J/yr; UEV= 1.11E+05 seJ/J (Odum et al., 2000); emergy= 6.60E+22 seJ/yr

**total emergy**= 1.51E+23 seJ/yr

**Biofuels**. ethanol= 2.71E+06 toe/yr (MME, 2010); energy= ethanol (toe/yr) * 4.19E+10 J/toe (IEA, 2011)= 1.13E+17 J/yr; UEV= 1.45E+05 seJ/J (Odum et al., 2000); emergy= 1.65E+22 seJ/yr

**Metals**

**ferroalloys**= 3.58E+11 g/yr (MME, 2010); UEV= 4.25E+06 seJ/g (Odum et al., 2000 (iron and steel products)); emergy= 1.52E+18 seJ/yr

**pig iron**= 6.30E+12 g/yr (MME, 2010); UEV= 5.43E+09 seJ/g (Bargigli and Ulgiati, 2003); emergy= 3.42E+22 seJ/yr

**aluminum**= 9.46E+11 g/yr (MME, 2010); UEV= 7.76E+08 seJ/g (Odum et al., 2000); emergy= 7.34E+20 seJ/y

**copper**= 1.35E+11 g/yr (MME, 2010); UEV= 3.36E+09 seJ/g (Brown and Ulgiati, 2004); emergy= 4.54E+20 seJ/yr

**zinc**= 4.05E+10 g/yr (MME, 2010); UEV= 1.14E+11 seJ/g (Odum et al., 2000); emergy= 4.62E+21 seJ/yr

**total emergy**= 4.00E+22 seJ/yr

**Minerals**. iron ore= 2.82E+14 g/yr (IBRAM, 2010); UEV= 2.22E+09 seJ/g (Buranakarn, 1998); emergy= 6.26E+23 seJ/yr

**Agriculture**

**cotton**= 4.63E+11 g/yr (FAO, 2008); UEV= 2.10E+10 seJ/g (Brandt-Williams, 2002); emergy= 9.72E+21 seJ/yr

**peanut**= 0.00E+00 g/yr (FAO, 2008)

**rice**= 2.02E+11 g/yr (FAO, 2008); UEV= 1.40E+09 seJ/g (Brown; Ulgiati, 2004); emergy= 2.83E+20 seJ/yr

**oat**= 9.60E+08 g/yr (FAO, 2008); UEV= 4.40E+09 seJ/g (Brandt-Williams, 2002); emergy= 4.22E+18 seJ/yr

**potato**= 1.33E+10 g/yr (FAO, 2008); UEV= 2.80E+09 seJ/g (Brandt-Williams, 2002); emergy= 3.72E+19 seJ/yr

**coffee**= 1.57E+12 g/yr (FAO, 2008); energy= coffee (g/yr) * 4.19 (kcal/g) (TACO, 2006) * 80% dry * 4186 (J/kcal)= 2.20E+16 J/yr; UEV= 1.54E+06 seJ/J (Odum et al., 2000); emergy= 3.39E+22 seJ/yr

**sugar**= 1.36E+13 g/yr (UNICA, 2011 (2008 harvest)); energy= sugar (g/yr) * 3.87 kcal/g (TACO, 2006) * 80% dry * 4186 (J/kcal)= 1.77E+17 J/yr; UEV= 1.51E+05 seJ/J (Odum et al., 2000); emergy= 2.67E+22 seJ/yr

**orange**= 2.12E+12 g/yr (FAO, 2008); UEV= 1.92E+09 seJ/g (Brandt-Williams, 2002); emergy= 4.07E+21 seJ/yr

**cassava**= 1.33E+10 g/yr (FAO, 2008); UEV= 1.62E+08 seJ/g (Rodrigues et al., 2003); emergy= 2.15E+18 seJ/yr

**corn**= 1.10E+13 g/yr (FAO, 2008); UEV= 7.98E+04 seJ/g (Odum et al., 2000); emergy= 8.78E+17 seJ/yr

**soybean**= 2.61E+13 g/yr (FAO, 2008); UEV= 9.87E+09 seJ/g (Brandt-Williams, 2002); emergy= 2.58E+23 seJ/yr

**wheat**= 6.44E+11 g/yr (FAO, 2008); energy= wheat (g/yr) * 3.60 (kcal/g) (TACO, 2006) * 80% dry * 4186 (J/kcal)= 7.76E+15 J/yr; UEV= 2.67E+05 seJ/J (Odum et al., 2000); emergy= 2.07E+21 seJ/yr

**total emergy**= 3.34E+23 seJ/yr

**Animal Products**

**meat**= 6.51E+11 g/yr (FAO, 2008); UEV= 4.85E+10 seJ/g (Brandt-Williams, 2002); emergy= 3.16E+22 seJ/yr

**milk**= 1.74E+12 g/yr (FAO, 2008); UEV= 3.37E+10 seJ/g (Brandt-Williams, 2002); emergy= 5.86E+22 seJ/yr

**eggs**= 2.41E+10 g/yr (FAO, 2008); UEV= 1.07E+11 seJ/g (Brandt-Williams, 2002); emergy= 2.58E+21 seJ/yr

**total emergy=** 9.28E+22 seJ/yr

**Fishery products.** fish= 5.82E+10 g/yr (IBAMA, 2007); UEV= 2.78E+11 seJ/g (Odum, 1996); emergy= 1.62E+22 seJ/yr

**Plastics**. plastics= 3.20E+10 g/yr (UN COMTRADE, 2010); UEV= 5.29E+09 seJ/g (Buranakarn, 1998); emergy= 1.69E+20 seJ/yr

**Chemicals**. chemicals= 9.45E+11 g/yr (UN COMTRADE, 2010); UEV= 6.38E+09 seJ/g (Odum, 1996 (fertilizer N)); emergy= 6.03E+21 seJ/yr

**Machinery and transport**. machines, vehicles, ships= 9.59E+11 g/yr (UN COMTRADE, 2010); UEV= 1.10E+10 seJ/g (Odum et al., 1987b); emergy= 1.05E+22 seJ/yr

**Refined goods**. glass, refined metals, wires, textiles= 2.58E+11 g/yr (UN COMTRADE, 2010); UEV= 2.69E+09 seJ/g (Buranakarn, 1998 (glass)); emergy= 6.93E+20 seJ/yr

**Electricity**. electricity= 5.90E+04 toe/yr (MME, 2010); electricity= (toe/yr) * 4.19E+10 J/toe (IEA, 2011)= 2.47E+15 J/yr; UEV= 3.36E+05 seJ/J (Odum et al., 2000); emergy= 8.30E+20 seJ/yr

**SERVICES**

GWP= 7.16E+13 US$/yr (CIA, 2008); PPP GDP= 1.98E+12 US$/yr (IMF, 2010); world emergy per dollar= 2.25E+12 seJ/US$ (Sweeney et al., 2007 modified); national emergy per dollar= 4.12E+12 seJ/US$ (this work)

**28.Imports**. value= 1.73E+11 US$/yr (BCB, 2011); emergy= 3.89E+23 seJ/yr (using world emergy per dollar)

**Exports**. value= 1.98E+11 US$/yr (BCB, 2011); emergy= 1.26E+24 seJ/yr (using national emergy per dollar)

## Italy, 2008

**RENEWABLE LOCAL SOURCES**

**1. Solar radiation.** land area= 3.01E+11 m2 (CIA, 2008); continental shelf area= 1.11E+11 m2 (WRI, 2000); radiation= 1.28E+02 kcal/cm2 (ENEA, 1989); land albedo= 0.20 (Henning, 1989); shelf albedo= 0.35 (Henning, 1989); land energy= land area (m2) * radiation (kcal/m2) * 1,00E+04 (cm2/m2) * 4186 (J/kcal) * (1-albedo)= 1.29E+21 J/yr; shelf energy= shelf area (m2) * radiation (kcal/m2) * 1E+04 (cm2/m2) * 4186 (J/kcal) * (1-albedo)= 3.84E+20; total energy= 1.67E+21 J/yr; UEV= 1 seJ/J (Odum, 1996); emergy= 1.67E+21 seJ/yr

**2. Deep heat.** land area= 3.01E+11 m2 (CIA, 2008); heat flow= 3.00E+06 J/m2 (estimated from Scatler et al., 1980); energy= land area (m2) * heat flow (J/m2)= 9.04E+17 J/yr; UEV= 5.76E+04 seJ/J= emergy= 5.21E+22 seJ/yr.

**3. Tide.** continental shelf area= 1.11E+11 m2 (WRI, 2000); average tide range= 0.30 m (IIM, 1992); number of tides= 2 #/day; seawater density= 1025 kg/m3; energy= continental shelf (m2) * 0.5 (half of tidal energy is supposed to be absorbed at the shelf) * #tides/yr * range^2 (m2) * 1025 (kg/m3) * 9.8 (m/s2) * 0,5= 3.65E+16 J/yr; UEV= 7.40E+04 seJ/J (Odum et al., 2000); emergy= 1.03E+21 seJ/yr

**4. Wind.** land area= 3.01E+11 m2 (CIA, 2008); wind velocity= 3.28 m/s (ISTAT, 2008); air density= 1.3 kg/m3; geostrophic wind= 5.2 m/s; drag coefficient= 3.00E-03; energy= density (kg/m3) * drag coefficient * geostrophic wind speed^3 (m3/s3) * land area (m2) * 3.15E+07 (s/yr)= 5.21E+18; UEV= 2.51E+03 (Odum et al., 2000)= 1.31E+22 seJ/yr

**5. Water**

**Rain's chemical potential.** continental shelf area= 1.11E+11 m2 (WRI, 2000); land area= 3.01E11 m2 (CIA, 2008); rain= 0.64 m (ISTAT, 2007); evapotranspiration rate from land= 0.436 (43.6% of total rainfall) (Henning, 1989); evapotranspired water= 0.28 m; energy on land= land area (m2) * evapotranspired water (m) * 1.00E+06 (g/m3) * 4.94 (J/g)= 4.14E+17 J/yr; energy on shelf= shelf area (m2) * evapotranspired water (m) * 1.00E+06 (g/m3) * 4.94 (J/g)= 3.49E+17 J/yr; total energy= 7.63E+17 J/yr; UEV= 6.61E+03 (this study)= 5.05E+21 seJ/yr

**Rain's geopotential enegy.** land area= 3.01E+11 m2 (CIA, 2008); rain= 0.64 (ISTAT, 2008); average elevation= 340 m (IGDA, 1975); runoff rate= 0.564 *56.4% of total rain); total runoff water= 0.36 m; water density= 1E+03 kg/m3; energy= land area (m2) * total runoff water (m) * water density (kg/m3) * average elevation (m) * gravity (m/s2)= 3.61E+17 J/yr; UEV= 1.40E+04 seJ/J (this study); emergy= 5.08E+21 seJ/yr

**6. Waves.** coastal length= 9.23E+06 m (WRI, 2003); component of length parallel to front wave= 4.20E+06 m; front wave energy= 2.20E+04 w/m (Couper, 1990); energy= parallel component of length (m) * front wave energy (W/m) * 3.15E+07 (s/yr)= 2.91E+18 J/yr; UEV= 5.12E+04 seJ/J (Odum et al., 2000); emergy= 1.49E+23 seJ/yr

**7. Marine currents.** not estimated for Italy

**Renewable flow=** 1.49E+23 seJ/yr (biggest renewable: waves)

**NON-RENEWABLE LOCAL SOURCES**

**8. Forest extraction**. According to ISTAT (2008), forest and protected areas are increasing in Italy, therefore forest extraction is considered zero.

**9. Fishery**. It is assumed that all fishery products in the Italian coast exceed the annual reproduction of fish, therefore total catch is considered nonrenewable. fish loss= 3.01E+11 g/yr (OCEAN2012, 2010); fish dry matter= 1.81E+11 g/yr; UEV= 2.78E+11 seJ/g (Odum, 1996); emergy= 1.27E+22 seJ/yr

**10. Water non-renewable extraction**. Scarce data.

**11. Soil loss: organic matter**. farm area subject to erosion= 1.27E+11 m2 (ISTAT, 2008); erosion rate of farmed area= 1.50E+03 g/m2 (EEA, 2001); % organic in soil= 3.00%; energy content= 5.00 kcal/g; net loss= farmed area (m2) * erosion rate (g/m2)= 1.191E+14 g; energy of net loss= net loss (g) * (% organic) * energy content (kcal/g) * 4186 (J/kcal)= 1.20E+17 J/yr; UEV= 1.24E+05 (Bargigli and Ulgiati, 2003)= 1.26E+22 seJ/yr

**12. Coal**. not estimated

**13. Natural gas.** Natural gas= 8.50E+09 m3/yr (BP, 2010); natural gas density= 7.89E+02 g/m3; mass of natural gas= 6.71E+12 g/yr; HHV of natural gas= 5.53E+04 J/g (Boustead and Hancock, 1979); energy= mass (g/yr) * HHV (J/g)= 3.71E+17 J/yr; UEV= 8.05E+04 seJ/J (Brown and Ulgiati, 2004); emergy= 3.25E+22 seJ/yr

**14. Oil**. oil= 5.20E+06 toe/yr (BP, 2010); energy= oil (toe/yr) * 4.19E+10 J/toe (IEA, 2011)= 2.18E+17 J/yr; UEV= 9.06E+04 seJ/J (Brown and Ulgiati, 2004); emergy= 1.93E+22 seJ/yr

**15. Minerals**

**feldspar=** 3.52E+12g/yr (ISTAT, 2008); UEV= 1.68E+09 seJ/g (Odum et al., 2000); emerg= 5.91E+21 seJ/yr

**bitumen and asphaltic rocks**= 1.09E+12 g/yr (ISTAT, 2008); UEV= 1.68E+09 seJ/g (Odum et al., 2000); emergy= 1.83E+21 seJ/yr

**potash, marine salts and salt rock**= 2.02E+12 g/yr (ISTAT, 2008); UEV= 1.68E+09 seJ/g (Odum et al., 2000); emergy= 3.68E+21 seJ/yr

**miscellaneous and other quarry products**= 1.59E+12 g/yr (ISTAT, 2008); UEV= 1.68E+09 seJ/g (Odum et al., 2000); emergy= 2.66E+21 seJ/yr

**aluminum silicates**= 6.30E+12 g/yr (ISTAT, 2008); UEV= 1.68E+09 seJ/g (Odum et al., 2000); emergy= 1.06E+22 seJ/yr

**other sand and gravel**= 3.32E+14 g/yr (ISTAT, 2008); UEV= 1.68E+09 seJ/g (Odum et al., 2000); emergy= 5.57E+23 seJ/yr

**marble**= 6.75E+12 g/yr (ISTAT, 2008); UEV= 2.43E+09 seJ/g (Odum et al., 2000); emergy= 1.64E+22 seJ/yr

**granite**= 2.17E+12 g/yr (ISTAT, 2008); UEV= 8.38E+09 seJ/g (Odum et al., 2000); emergy= 1.82E+21 seJ/yr

**sandstone and other building stone**= 1.16E13 g/yr (ISTAT, 2008); UEV= 1.68E+09 seJ/g (Odum et al., 2000); emergy= 1.94E+22 seJ/yr

**limestone and dolomite**= 4.53E+13 g/yr (ISTAT, 2008); UEV= 1.68E+09 seJ/g (Odum et al., 2000); emergy= 7.60E+22 seJ/yr

**16. Metals.** not estimated

**IMPORTS**

**17. Fuels**

**oil**= 8.33E+07 toe/yr (ISTAT, 2008); energy= oil (toe/yr) * 4.19E+10 J/toe (IEA, 2011)= 3.49E+18 J/yr; UEV= 9.06E+04 seJ/J (Brown and Ulgiati, 2004); emergy= 3.10E+23 seJ/yr

**coal**= 2.62E+10 kg/yr (ISTAT, 2008); energy= 3.23E+18 J/yr; UEV= 6.71E+04 seJ/J (Brown and Ulgiati, 2004); emergy= 7.05E+22 seJ/yr

**natural gas**= 5.83E+10 kg/yr (ISTAT, 2008); HHV of natural gas= 5.53E+04 J/g (Boustead and Hancock, 1979); energy= natural gas (kg/yr) * HHV (J/g)= 3.23E+18 J/yr; UEV= 8.05E+04 seJ/J (Brown and Ulgiati, 2004); emergy= 2.82E+23 seJ/yr

**total emergy**= 6.62E+23 seJ/yr

**18. Metals**

**metallic minerals**= 1.94E+13 g/yr (ISTAT, 2008); UEV= 1.68E+09 seJ/g (Odum et al., 2000); emergy= 3.25E+22 seJ/yr

**metallic scraps**= 1.86E+12 g/yr (ISTAT, 2008); UEV= 4.42E+09 seJ/g (Odum, Arding, 1991); emergy= 8.24E+21 seJ/yr

**steel and pig iron**= 2.61E+13 g/yr (ISTAT, 2008); UEV= 5.30E+09 seJ/g (Bargigli and Ulgiati, 2003); emerg= 1.38E+23 seJ/yr

**gold**= 2.53E+08 g/yr (ISTAT, 2008); UEV= 8.38E+11 seJ/g (Cohen et al., 2007); emergy= 2.12E+20 seJ/yr

**copper and zinc alloys**= 1.31E+12 g/yr (ISTAT, 2008); UEV= 1.14E+11(Odum and Arding, 1991); emergy= 1.50E+23 seJ/yr

**total emergy**= 2.89E+23 seJ/yr

**19. Minerals**. minerals= 3.77E+13 g/yr (ISTAT, 2008); UEV= 1.68E+09 seJ/g (Odum, 1996); emergy= 6.84E+22 seJ/yr

**20. Agriculture=** 1.55E+10 kg/yr (ISTAT, 2008); dry matter= 7.77E+09 kg/yr; UEV= 1.11E+09 seJ/g (Zucaro et al., 2010); emergy= 8.62E+21 seJ/yr

**21. Animal products=** 5.71E+11 g/yr (ISTAT, 2008); energy= products (g/yr) * 0.22 (organic) * 5.00 (kcal/g) * 4186 (J/kcal)= 2.63E+15 J/yr; UEV= 5.31E+06 seJ/J (Ulgiati et al., 1994); emergy= 1.40E+22 seJ/yr

**22. Fishery products**. fish= 1.97E+11 g/yr (ISTAT, 2008); energy= fish (g/yr) * 0.22 (organic) * 5.00 (kcal/g) * 4186 (J/kcal)= 9.09E+14 J/yr; UEV= 3.35E+06 seJ/J (Odum and Arding, 1991); emergy= 3.05E+21 seJ/yr

**23. Plastics**. plastics= 1.90E+12 g/yr (ISTAT, 2008); UEV= 7.21E+09 seJ/g (Odum, Odum, 1983); emergy= 1.37E+22 seJ/yr

**24. Chemicals**. chemicals= 2.16E+13 g/yr (ISTAT, 2008); UEV= 6.37E+08 seJ/g (Odum and Odum, 1983); emergy= 1.38E+22 seJ/yr

**25. Machinery and transport.** machinery and transport= 9.06E+12 g/yr (ISTAT, 2008); UEV= 1.12E+10 seJ/g (Odum et al., 1987b); emergy= 1.02E+23 seJ/yr

**26. Refined goods**

**leather**= 8.72E+11 g/yr (ISTAT, 2008); energy content= 1.50E+07 BTU/ton (Odum and Odum 1987); energy= 1.38E+16 J/yr; UEV= 1.44E+07 seJ/J (Odum and Odum, 1987); emergy= 1.99E+23 seJ/yr

**textiles**= 1.15E+12 g/yr (ISTAT, 2008); energy content= 1.50E+07 BTU/ton (Odum and Odum, 1987); energy= 1.82E+16 J/yr; UEV= 6.37E+06 seJ/J (Odum and Odum, 1987); emergy= 1.16E+23 seJ/yr

**wood industry**= 5.04E+12 g/yr (ISTAT, 2008); energy content= 4.00 kcal/g; energy= 8.44E+16 J/yr; UEV= 5.85E+04 seJ/J (Odum and Arding, 1991); emergy= 2.23E+21 seJ/yr

**total emergy**= 3.81E+23 seJ/yr

**27. Electricity**. electricity= 4.30E+10 kWh/yr (EIA, 2008); electricity= (kWh/yr) * 3.60E+06 (J/kWh) (IEA, 2011)= 1.55E+17 J/yr; UEV= 3.36E+05 seJ/J (Odum et al., 2000); emergy= 3.89E+22 seJ/yr

**EXPORTS**

**Fuels**

**oil**= 1.20E+06 toe/yr (ISTAT, 2008); energy= oil (toe/yr) * 4.19E+10 (J/toe) (IEA, 2011)= 5.00E+16 J/yr; UEV= 9,06E+04 seJ/J (Brown and Ulgiati, 2004); emergy= 4.45E+21 seJ/yr

**coal**= 3.21E+10 g/yr (ISTAT, 2008); energy= 8.04E+14 J/yr; UEV= 6.71E+04 seJ/J (Brown and Ulgiati, 2004); emergy= 8.63E+19 seJ/yr

**total emergy**= 4.53E+21 seJ/yr

**Metals**

**metallic minerals**= 1.82E+11 g/yr (ISTAT, 2008); UEV= 1.68E+09 seJ/g (Odum et al., 2000); emergy= 3.05E+20 seJ/yr

**metallic scraps**= 4.22E+12 g/yr (ISTAT, 2008); UEV= 4.42E+09 seJ/g (Odum and Arding, 1991); emergy= 1.87E+22 seJ/yr

**steel and pig iron**= 1.79E+13 g/yr (ISTAT, 2008); UEV= 5.30E+09 seJ/g (Bargigli and Ulgiati, 2003); emergy= 9.47E+22 seJ/yr

**gold**= 1.72E+08 g/yr (ISTAT, 2008); UEV= 8.38E+11 seJ/g (Cohen et al., 2007); emergy= 1.44E+20 seJ/yr

**copper and zinc alloys**= 6.66E+11 g/yr (ISTAT, 2008); UEV= 1.14E+11(Odum and Arding, 1991); emergy= 7.60E+22 seJ/yr

**total emergy**= 2.12E+23 seJ/yr

**Minerals**. minerals= 4.38E+12 g/yr (ISTAT, 2008); UEV= 1.68E+09 seJ/g (Odum, 1996); emergy= 7.35E+21 seJ/yr

**Agriculture products=** 5.01E+09 kg/yr (ISTAT, 2008); dry matter= 2.51E+09 kg/yr; UEV= 1.11E+09 seJ/g (Zucaro et al., 2010); emergy= 2.78E+21 seJ/yr;

**Animal products**= 4.73E+10 g/yr (ISTAT, 2008); energy= products (g/yr) * 0.22 (organic) * 5.00 (kcal/g) * 4186 (J/kcal)= 2.18E+14 J/yr; UEV= 5.31E+06 seJ/J (Ulgiati et al., 1994); emergy= 1.16E+21 seJ/yr

**Fishery products.** fish= 6.88E+10 g/yr (ISTAT, 2008); energy= fish (g/yr) * 0.22 (organic) * 5.00 (kcal/g) * 4186 (kcal/J)= 3.17E+14 J/yr; UEV= 3.35E+06 seJ/J (Odum and Arding 1991); emergy= 1.06E+21 seJ/yr

**Plastics**. plastics= 3.59E+12 g/yr (ISTAT, 2008); UEV= 7.21E+09 seJ/g (Odum and Odum, 1983); emergy= 2.59E+22 seJ/yr

**Chemicals**. chemicals= 1.43E+13 g/yr (ISTAT, 2008); UEV= 6.37E+08 seJ/g (Odum and Odum, 1983); emergy= 9.12E+21 seJ/yr

**Machinery and transport**. machinery and transport= 8.40E+12 g/yr (ISTAT, 2008); UEV= 1.12E+10 seJ/g (Odum et al., 1987b); emergy= 9.43E+22 seJ/yr

**Refined goods**

**leather**= 6.07E+11 g/yr (ISTAT, 2008); energy content= 1.50E+07 BTU/ton (Odum and Odum, 1987); energy= 9.61E+15 J/yr; UEV= 1.44E+07 seJ/J (Odum and Odum, 1987); emergy= 1.38E+23 seJ/yr

**textiles**=1.04E+12 g/yr (ISTAT, 2008); energy content= 1.50E+07 BTU/ton (Odum and Odum, 1987); energy= 1.64E+16 J/yr; UEV= 6.37E+06 seJ/J (Odum and Odum, 1987); emergy= 1.04E+23 seJ/yr

**wood industry**= 9.30E+11 g/yr (ISTAT, 2008); energy content= 4.00 kcal/g; energy= 1.40E+16 J/yr; UEV= 5.85E+04 seJ/J (Odum and Arding, 1991); emergy= 8.20E+20 seJ/yr

**total emergy**= 2.44E+23 seJ/yr

**Electricity**. electricity= 3.43E+09 kWh/yr (EIA, 2008); energy= (kWh/yr) * (3.60E+06 J/kWh)= 1.24E+16 J/yr; UEV= UEV= 3.36E+05 seJ/J (Odum et al., 2000); emergy= 3.11E+21 seJ/yr

**SERVICES**

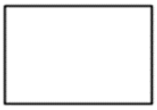
GWP= 7.16E+13 US$/yr (CIA, 2008); PPP GDP= 1.81E+12 US$/yr (IMF, 2010); world emergy per dollar= 2.25E+12 seJ/US$ (Sweeney et al., 2007 modified); national emergy per dollar= 1.86E+12 seJ/US$ (this work)

**28. Imports**. value= 5.03E+11 US$/yr (ISTAT, 2008); emergy= 1.13E+24 seJ/yr (using world emergy per dollar)

**Exports**. value= 4.61E+11 US$/yr (ISTAT, 2008); emergy= 8.58E+23 seJ/yr (using national emergy per dollar)

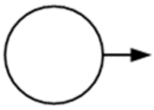
## USE OF ENERGY SYSTEM SYMBOLS.

(From: Odum, H.T., 1996. "Environmental Accounting". J. Wiley.)



System Frame:

A rectangular box is drawn to represent the boundaries that are selected.



Source:

Any input that crosses the boundary is a source, including pure energy flows, materials, information, genes, services and inputs that are destructive.

Pathway Line:

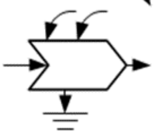
Any flow is represented by a line, including pure energy, materials and information. Money is shown with dashed lines.

Heat sink:

This symbol represents the dispersal of available energy (potential energy) into a degraded, used state, not capable of further work.

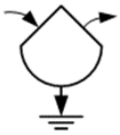
Split:

A pathway that branches represents a split of flow into two of the same type.



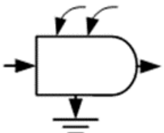
Interaction:

Two or more flows that are different and both requires for a process are connected to an "interaction" symbol. The output of an interaction is an output of an production process, a flow of product.



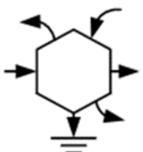
Storage tank:

Any quantity stored within the system is given a "tank" symbol, including materials, pure energy, money, assets, information, image and quantities that are harmful to others. Every flow in or out of a tank must be the same type of flow and mesured in the same units.



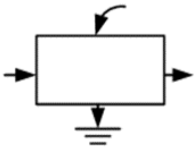
Producers:

"Producer" symbols are used for units on the left side of the systems diagram that receive commodities and other inputs of different types interacting to generate products.



Consumers:

"Consumer" symbols are used for units on the right side of the system diagram that receive products and feedback services and materials.



Miscellaneous Box:

The rectangular box is used for any subsystem structure and/or function.

Small Box:

A very small box on a pathway is used to initiate another circuit that is driven by "force" in proportion to the pathway.

Exchange transaction:

Where quantities in one flow are exchange for those of anoher, the "transaction" symbol is used. Most often the exchange is a flow of commodities, goods or services echanged for money (drawn with dashed lines).

# CHAPTER 13 –GLOBAL AND SECTOR-BASED FOCUS ON ENERGY EFFICIENCY IN ITALY

*Introduction*

After the Paris Agreement in 2015, decarbonization has been the keyword for European economies, at least on a formal level. In 2015 EU published a document called Energy Union strategy, based on 5 pillars: energy security, lowering demand through energy efficiency, improving internal market, decarbonization of economy, research and innovation. Major focus in energy efficiency is put on the building sector, which accounts for around 40% of final energy consumption in EU. This is one of the reasons why Italy adopted Minimum Requirements Decree, the new national reference for energy efficiency in buildings.

*National outlook*

Consistently with the decreasing trend observed since 2010, in 2014 gross inland consumption decreased by 5.3%, reaching 151 Mtoe. The GDP shows a very similar trend in 2013 (-0.3%). Primary energy intensity reflects these two trends: since 2008 it has decreased by 17.3% (Figure 1) and in 2014 it was equal to 98.4 toe/M€2010, decreasing by 5% compared to 2013.

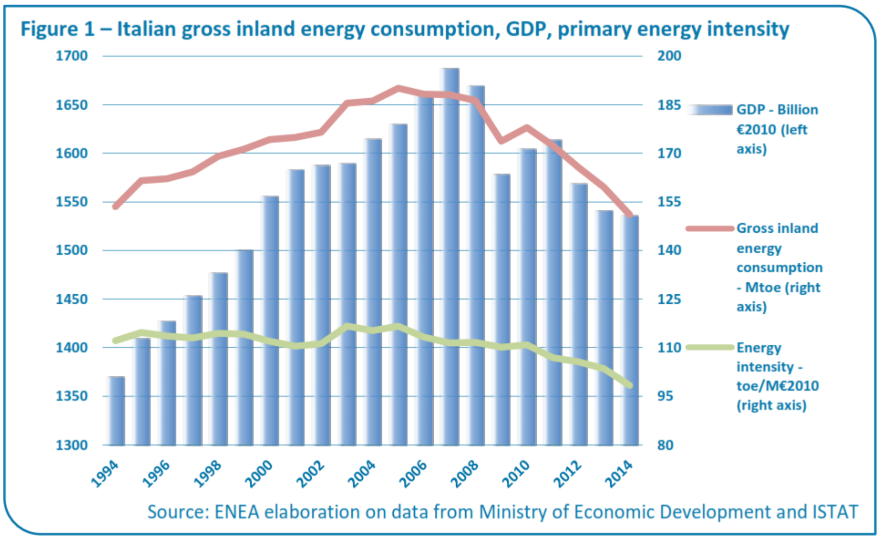



**Figure 4.** Italian gross inland energy consumption, GDP, primary energy intensity.

In Italy, the primary energy intensity is lower than the average in EU28 (-18.5%) and in Eurozone countries (-15%) (Figure 2).

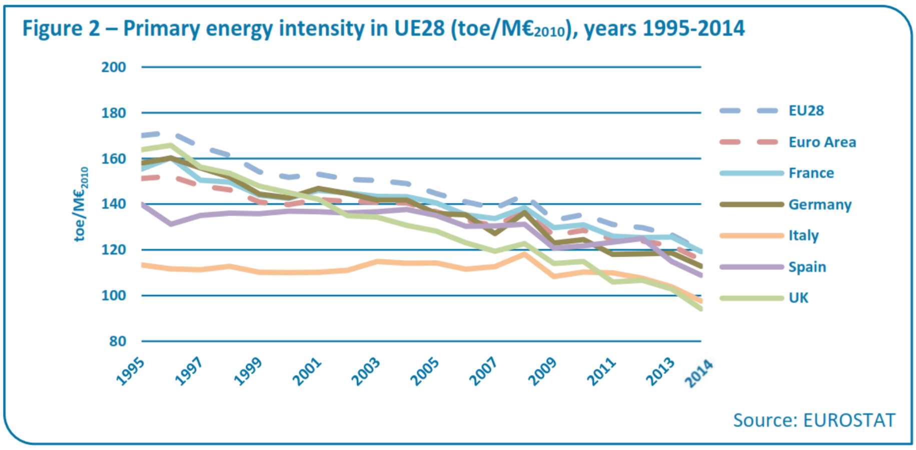



**Figure 5.** Primary energy intensity in UE28 (toe/M€$_{2010}$), years 1995-2014.

Looking through the sectors, residential and services decrease by -11.6%, compared to 2013; industry lowers by -2.4%; transport is the only one growing (+3.6%). In spite of the decrease observed in 2014, the highest consumption share still corresponds to the civil sector (37.1%), followed by transport (33.3%) and industry (21.3%). Such a distribution is determined by the steady growth in the civil sector over the 1994-2014 period, which implied an energy consumption higher than the 1994 level (+33.8%). By contrast, the industrial sector lowered its consumption (-26.5%), in particular starting from 2000. A reduction is also observed in the agricultural sector (-14.6%). The transport sector shows a slight increase (6.6%) in the 1994-2004 period (Figure 3).

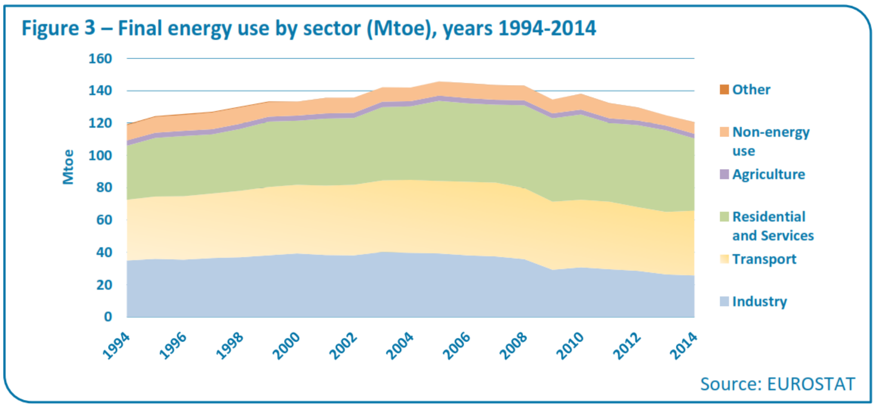



**Figure 6.** Final energy use by sector ($M_{toe}$), years 1994-2014.

European project ODYSSEE-MURE developed the “ODEX” energy efficiency index, which can be used for an overall evaluation of energy efficiency improvements in different sectors. It provides a more reliable assessment than energy intensity figures, since it does not include structural changes and other factors not associated to efficiency (Figure 4).

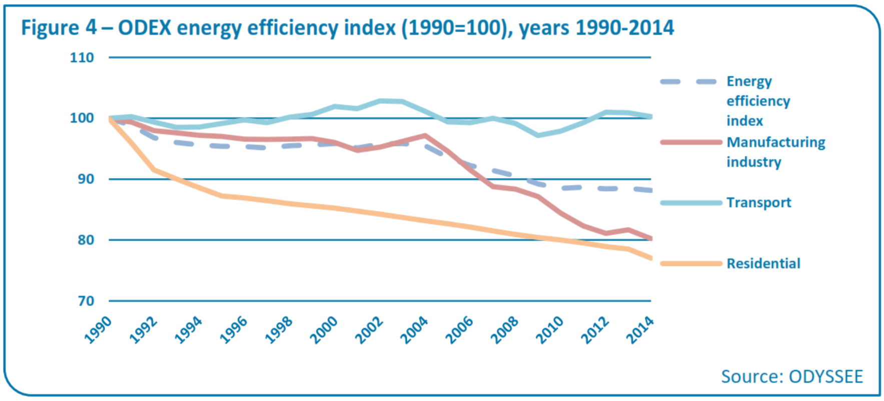



**Figure 7.** ODEX energy efficiency index (1990=100), years 1990-2014.

In 2014, the ODEX index (lower the value, better the performance) for the whole Italian economy was 88.1, slightly decreasing after the constant trend observed in the last three years and the steady improvements until 2010. Sectors have contributed to this trend in a different way: the residential sector registered regular and constant progresses over the 1990-2014 period, with main progresses in the early Nineties; the industrial sector has obtained significant improvements starting from 2005, with a negative result in 2013 associated to a slight efficiency loss in non-metallic minerals (excluded cement) and textile. The transport sector has the greatest difficulties in achieving energy efficiency improvements due to the characteristics of the freight transport system, almost exclusively based on road transport. In particular, both number of travels and energy consumption are growing, although with a lower load factor.

*Achieved energy savings*

Energy efficiency obligation scheme or White Certificates (Table 1): the energy saving from projects implemented since 2005 through standard sheets (ex-ante estimation based on algorithms), and analytical and final balance sheets (ex-post measure) was equal to more than 4.75 Mtoe/year of primary energy (equivalent to more than 4.38 Mtoe/year of final energy).

**Table 3.** Savings from White Certificates (primary energy, Mtoe/year), years 2005-2015.

**Table 1 – Savings from White Certificates (primary energy, Mtoe/year), years 2005-2015**

| | Total 2005-2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total 2005-2015 |
|---|---|---|---|---|---|---|---|
| Total | 2.62 | 0.07 | 0.30 | 0.79 | 0.53 | 0.44 | 4.75 |

Source: Ministry of Economic Development elaboration on Gestore Servizi Energetici (GSE) data

Fiscal deductions for energy renovation of existing buildings: the energy saving for 2015 has then been estimated on the basis of preliminary data and was equal to 0.24 Mtoe/year of primary and final energy. The overall energy saving in primary and final energy was equal to 1.89 Mtoe/year (Table 2). In the 2007-2015 period, more than 2.5 million interventions were incentivized, with more than 28 billion euros invested by households.

Transport sector (Table 2): a primary energy saving equal to 1.44 Mtoe/year (equal to 1.33 Mtoe/year of final energy) was achieved by applying incentives to the purchase of more efficient vehicles; implementing EC Regulations; and commissioning high speed railways, which implied a demand reduction on the corresponding flight and road routes.

**Table 4.** Savings from measures in transport sector (primary energy, Mtoe/year), years 2005-2015.

Table 2 – Savings from measures in transport sector (primary energy, Mtoe/year), years 2005-2015

| Measure | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015* | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| 2007-2009 incentives for new cars | 0.03 | 0.04 | 0.14 | 0 | 0 | 0 | 0 | 0 | 0 | 0.21 |
| EC Regulation 443/2009 | | | | 0.16 | 0.17 | 0.16 | 0.21 | 0.22 | 0.2 | 1.12 |
| EC Regulation 510/2011 | | | | | | | 0.003 | 0.01 | 0.01 | 0.023 |
| Incentives for low emission vehicles | | | | | | | 0.0002 | 0 | 0 | 0.0002 |
| High speed railways | | 0.01 | 0.04 | 0 | 0.01 | 0 | 0.004 | 0.014 | 0.01 | 0.088 |
| Total | 0.03 | 0.05 | 0.18 | 0.16 | 0.18 | 0.16 | 0.217 | 0.244 | 0.22 | 1.441 |

* Estimates

Source: ENEA elaboration

For the 2005-2016 time horizon, as in the 2011 NEEAP, total final energy saving deriving from analyzed measures amounts to almost 10 Mtoe/year, that is 91.2% of 2016 target. This implies an annual cumulative saving of about 3 billion euros of avoided oil and natural gas imports (Figure 5).

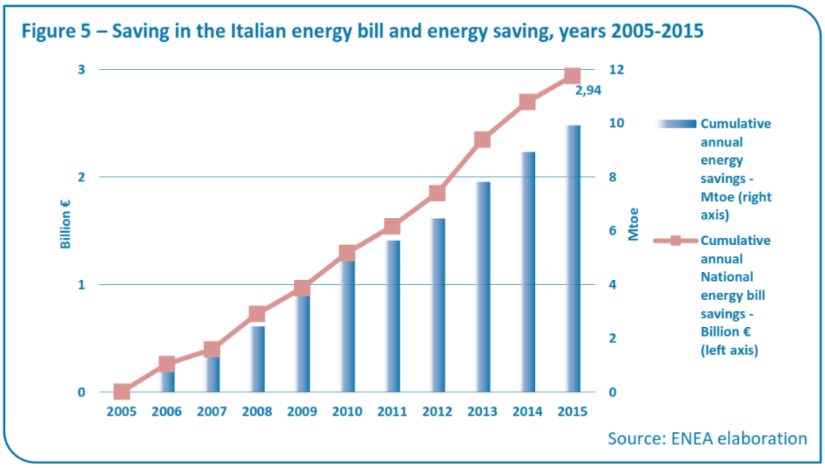



**Figure 8.** Saving in the Italian energy bill and energy saving, year 2005-2015.

*Industry*

In 2013 the energy consumption in industry fell to 27.8 Mtoe, -8.1% compared to 2012. The energy consumption decreased all over the period 2000-2013, -30.5%, and the slight growth in 2010 was blocked by the financial crisis on credit market and public budget, started in 2011. The performance in industry depends on manufacturing industry: -8.2% of energy consumption in 2013 compared to 2012, -32.6% over the period 2000-2013. In 2013 all industrial branches had a reduction in energy consumption compared to 2012, with peaks observed for steel, -

19.1%, non-ferrous metals, -16.3%, and paper, -14.3%, with the exception of chemicals, +0.2%. Over the period 2000-2013 for almost all industrial branches were observed decreases greater than 30% (Figure 6): -56.9% for textiles, -38.3% for non-metallic minerals and -33.8 for non-ferrous metals, exceptions were -23.5% for paper, -24.0% for food and -25.8% for steel. Industrial production decreased in the period but less than the energy consumption as evidence of improvement in energy efficiency.

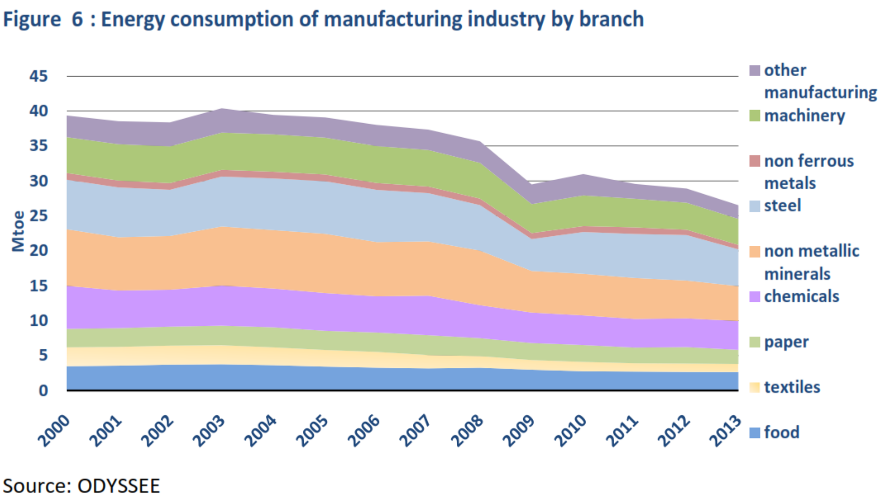



**Figure 9.** Energy consumption of manufacturing industry by branch.

In 2013 the energy-intensive branches absorbed almost two-thirds (64.2%) of the total energy consumption of industry: a fifth was consumed by primary metals, followed by non-metallic minerals, 17.9%, chemicals, 14.8%, and paper, 7.3%. The other industrial branches have used less than 10%, except for machinery (13.4%) (Figure 7).

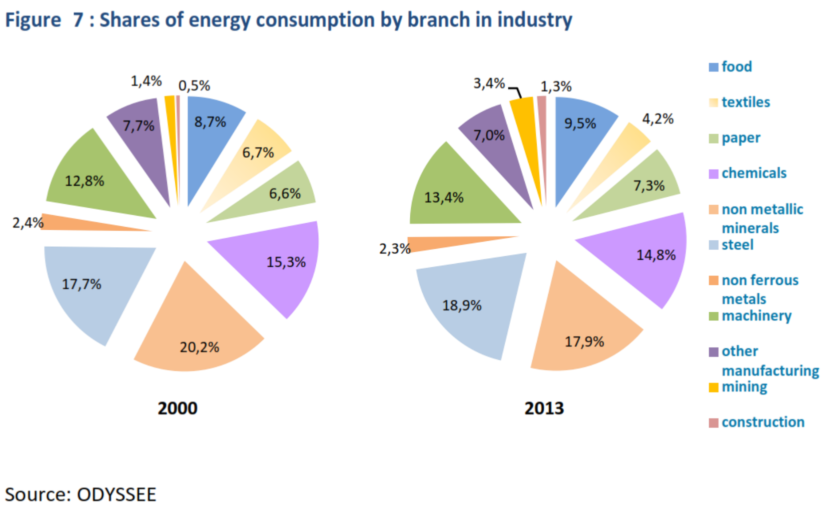
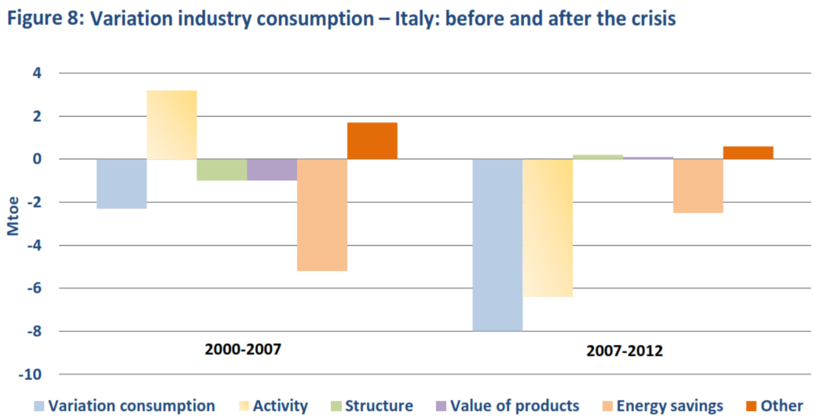



**Figure 10.** Shares of energy consumption by branch in industry.

The decrease in energy consumption in the period 2000-2012 is mainly determined by improvement in energy efficiency and the reduction of the activity, especially since 2007 because of the crisis. Before the crisis, the improvement in energy efficiency was counterbalanced by the activity effect. After the crisis, the main driver to the reduction in energy consumption was the activity effect that in addition to the improvement in energy efficiency has led to a drop of about 9 Moe. Value of products and structural effects had a marginal impact. In the Figure 8 is shown the variation of energy consumption before and after the crisis.

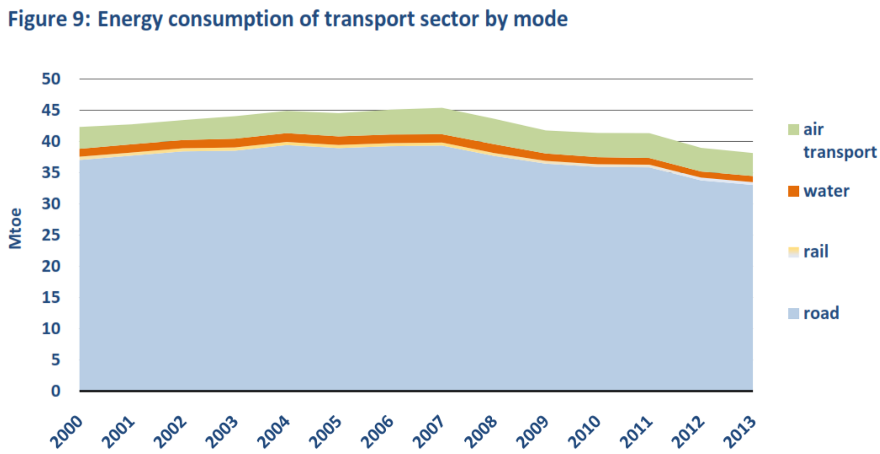



Source: ODYSSEE

**Figure 11.** Variation industry consumption – Italy: before and after the crisis.

*Transport*

In 2013 the energy consumption of transport sector amounted to 38.2 Mtoe, -2.3% compared to 2012. The road transport is the main mode, both for passenger and freight transport: in 2013 it absorbed 86.6% of energy consumption of transport sector (in slight decrease in the last years), followed by air transport (international air transport included), 9.7%, and water transport, 2.6 (Figure 9).




Source: ODYSSEE

**Figure 12.** Energy consumption of transport sector by mode.

Since 2007 the energy consumption has started to decrease because of the economic crisis: -15.8% since 2007 and -9.7% over the period 2000-2013. The variation in energy consumption is due to a reduction in the passenger and freight traffic, measured in passenger-km and tonne-km (activity effect), and changes in energy consumption per passenger-km and tonne-km (energy savings): the energy consumption per passenger-km is decreasing because of decrease in the energy specific consumption; the energy consumption per tonne-km is rising because of the increase in travels but less goods transported per travel (Figure 10).

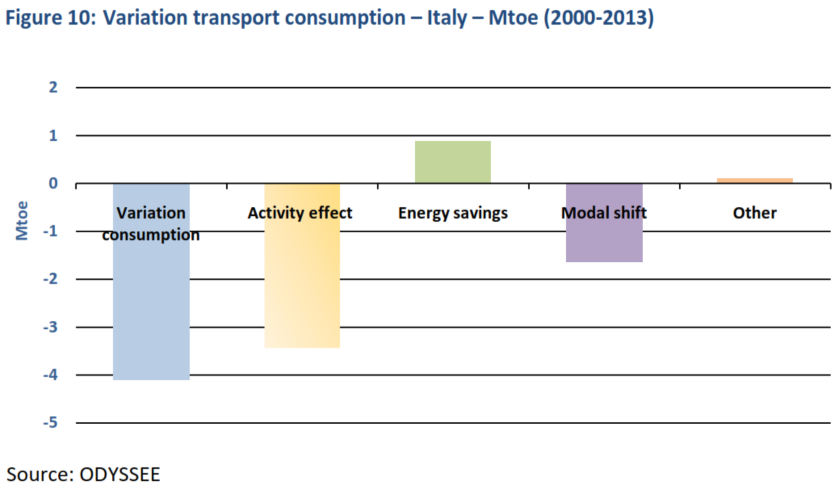



**Figure 13.** Variation transport consumption – Italy – Mtoe (200-2013).

Over the period 2000-2013 the energy consumption of road transport decreased by 10.8%: cars consumption reduced by 23.0% because of new cars more efficient, shift from gasoline cars to other type of cars and the economic crisis of 2007, while the other road transport modes had an increase in energy consumption (Figure 11).

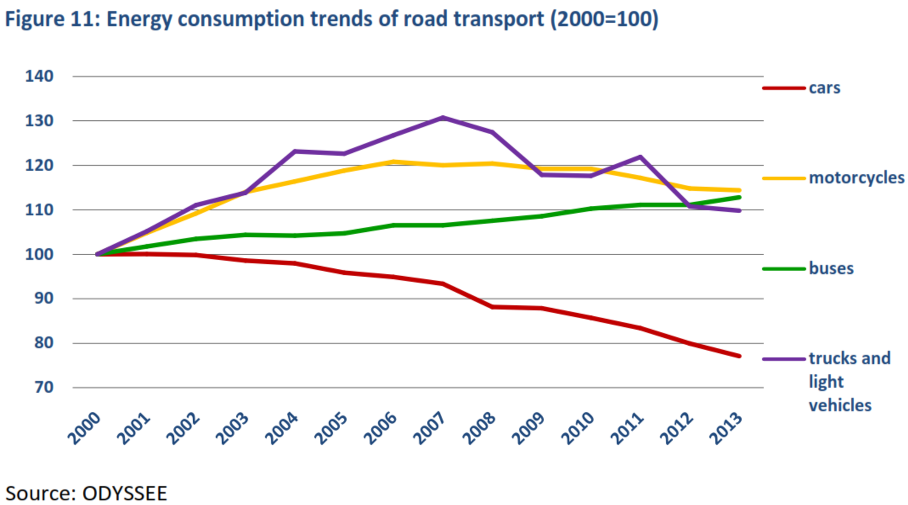



**Figure 14.** Energy consumption trends of road transport (2000=100).

The energy efficiency index of transport sector in 2013 was 87.2, with an improvement of 12.8% in the period 2000-2013 (Figure 12). The efficiency of transport sector depends mainly on the energy efficiency of transport road because cars and trucks take up almost 90% of energy consumption: over the period 2000-2013 the energy efficiency of cars improved by 15.8% while energy efficiency of trucks worsened by 59.0%. The other transport modes have improved in energy efficiency but their impact is limited: 46.9% for water transport, 33.4% for air transport and 10.3% for rail in the period 2000-2013.

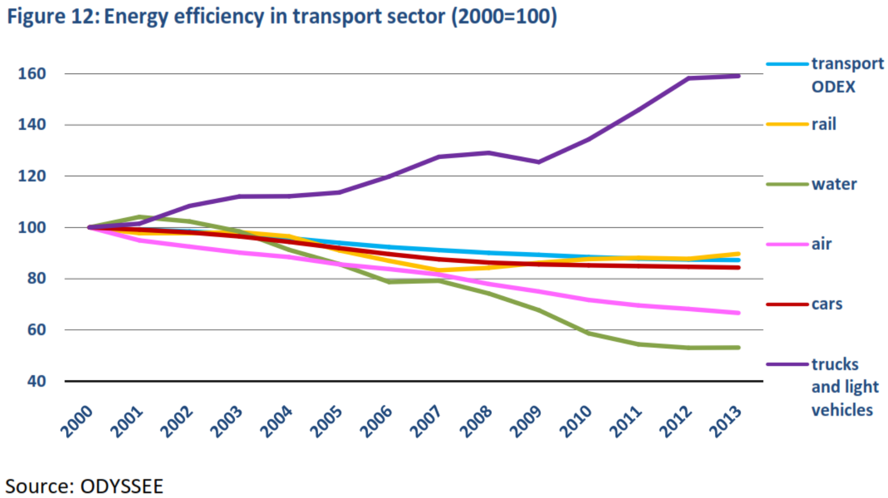



**Figure 15.** Energy efficiency in transport sector (2000=100).

*Household and services*

In 2013 the energy consumption of households amounted to 30.1 Mtoe, stable compared to 2012. The household consumption increased until to 2010 with an annual growth rate of 2.7%, followed by a high drop of 12.5% in 2011 and a rise in 2012: +21.7% over the period 2000-2013 (Figure 13). The main energy source is natural gas with a share of 6.7% in 2013 and +11.8% over the period 2000-2013.

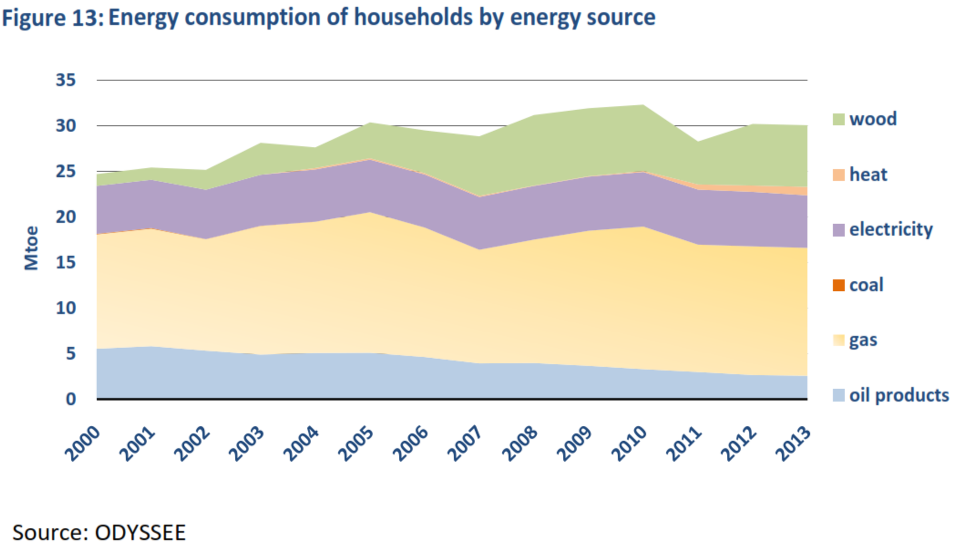



**Figure 16.** Energy consumption of households by energy sources.

In 2013 the energy consumption for air conditioning (space heating and air cooling) took for approximately 75% of the total consumption (Figure 14), increasing in recent years. Energy consumption for lighting and electrical appliances, like as for cooking and hot water, had a constant trend over the period, slightly down in the last years: in 2013 the share of consumption was 10.9% for lighting and electrical appliances, 8.5% for hot water and 5.5% for cooking.

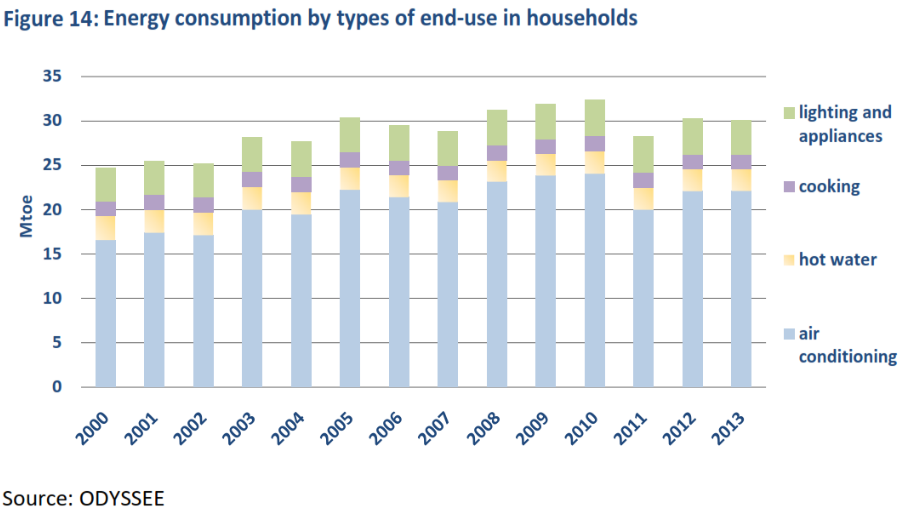



**Figure 17.** Energy consumption by types of end-use in households.

Energy efficiency in households over the period 2000-2013 improved only by 7.5% (Figure 15). The slowdown is due to an increase in energy consumption for space heating and not of loss in energy efficiency: a high raise in wood consumption, especially related to the second residences, and expansion of the natural gas network.

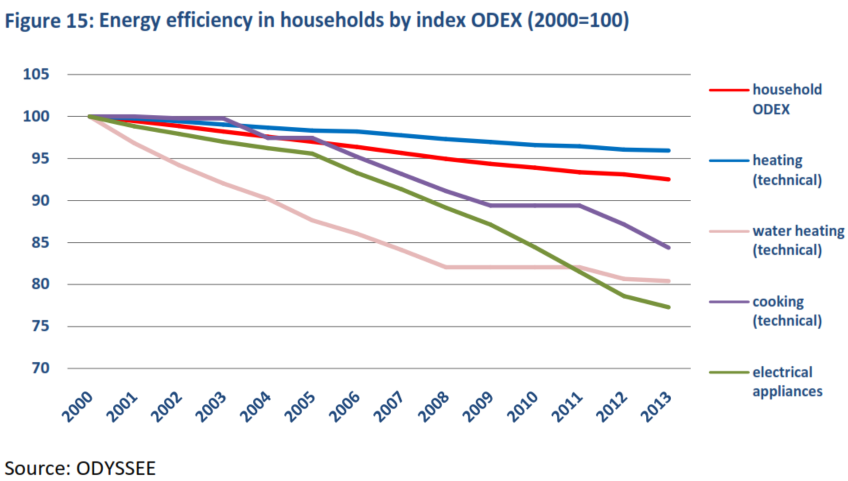



**Figure 18.** Energy efficiency in households by index ODEX (2000=100).

In 2013 the energy consumption of services was 20.1 Mtoe. The main energy sources are natural gas and electricity with a share, respectively, of 56.5% and 38.2%. The services sector is the leading sector of overall economy: in the period 2000-2013 it has showed a highest increase in energy consumption, +39.1%, confirmed by the growth in energy intensity, total (+32.9%) and electricity (+50.2%), and in energy consumption per employee, total (+30.3%) and electricity (+47.3%) (Figure 16).

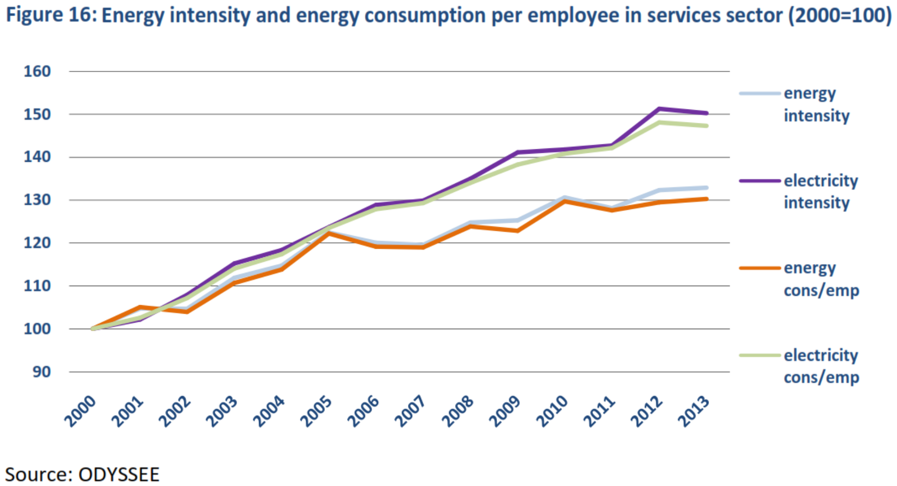



**Figure 19.** Energy intensity and energy consumption per employe in services sector (2000=100).

*Agriculture*

In 2013 the energy consumption in agriculture was 2.8 Mtep: -1.4% compared to 2012 and -12.0% over the period 2000-2013. The main energy sources are oil products that absorbs the 75.6% of total energy consumption. In the period 2000-2013 all components of agriculture decreased (Figure 17): production -4.0%, value added -4.3% and, consequently, the intensity was reduced by 8.0%.

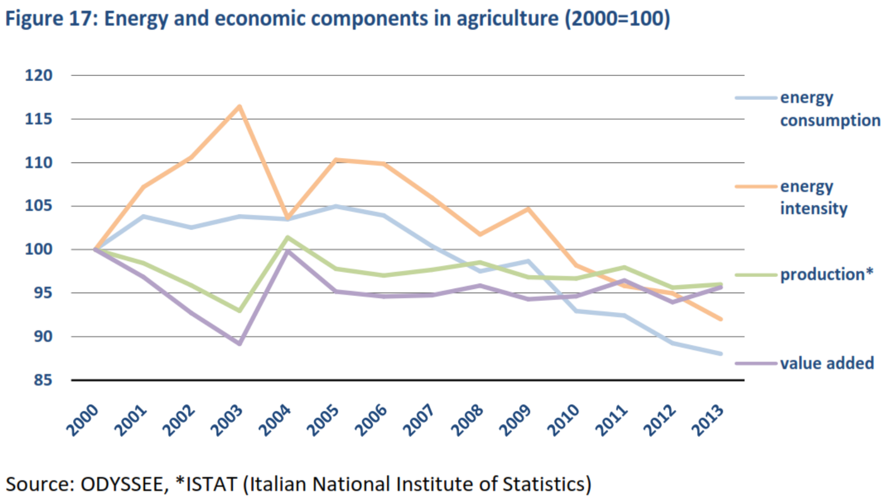



**Figure 20.** Energy and economics components in agriculture (2000=100).

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