EUFORIE
European Futures for Energy Efficiency

Assessment of costs and benefits of energy efficiency solutions

Work Package 3 - Deliverable 3.3

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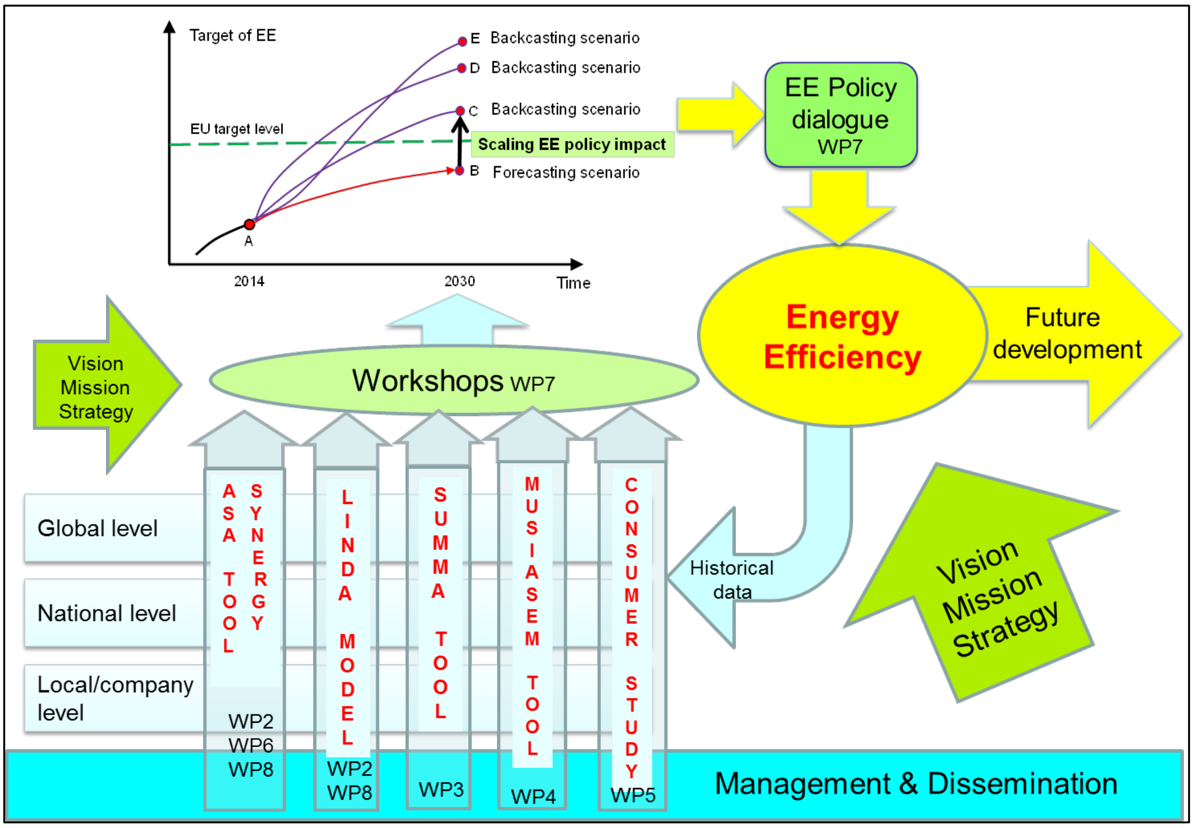
The EUFORIE project

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.

Assessment of costs and benefits of energy efficiency solutions.



Contents

4. Chapter 4 – System level. Urban energy metabolism, the case study of the City of Napoli p. 62

5. Appendix p. 81

This Appendix includes two papers (Sections 5.1 and 5.2) published within the EUFORIE project, representing the follow up of the integration process of the approaches dealt with in the project. In particular, they deal with application of the MuSIASEM approach, to provide a clear example of how it works, as a follow up of the description provided in Deliverable D3.1.

These papers should be looked at jointly with the paper about Napoli, included in Deliverable D3.1 Chapter 10 (Silvio Viglia, Dario Felice Civitillo, Gianluca Cacciapuoti, Sergio Ulgiati, Indicators of environmental loading and sustainability of urban systems. An emergy-based environmental footprint. Ecological Indicators, 94(3): 82-99), in order to provide a picture of potential integration for the investigation of the same kind of system.

The third paper included in this Appendix (Section 5.3) aims at providing a number of results from the application of the SUMMA approach to different systems. This paper shows patterns of integration of Exergy, Material Flow Accounting, Emergy, Life Cycle Assessment). It is not a result of the EUFORIE Project, but instead of the previous SMILE Project. It was included here to provide a clear example of how SUMMA works, as a follow up of the description provided in Deliverable D3.1.

5.1 An application of the MuSIASEM approach to an urban system (Barcelona)

Laura Pérez Sánchez, Maddalena Ripa, Raúl Velasco-Fernández, Gonzalo Gamboa, Renato F. Rallo, Mario Giampietro, 2017. Energy performance at city level − the societal metabolism of Barcelona. In: Book of Proceedings of the 10th Biennial International Workshop "Advances in Energy Studies", BIWAES, edited by S. Ulgiati and L. Vanoli, Napoli, September 25-28, 2017 Technical University of Graz Publisher - Pp. 772

5.2 A comparison of two urban systems (Napoli and Hongkong) via the MuSIASEM approach

Renato F. Rallo, Amalia Zucaro, 2019. Assessing the Energy Metabolism of Urban Systems: A Comparison of Napoli and Hong Kong Through the MuSIASEM Approach. Journal of Environmental Accounting and Management 7(2): 189-201

5.3 The SUMMA approach. Rationale, methodological aspects and results

Ulgiati, S., Ascione, M., Bargigli, S., Cherubini, F., Franzese, P.P., Raugei, M., Viglia, S., Zucaro, A., 2011. Material, Energy and Environmental Performance of Technological and Social Systems under a Life Cycle Assessment Perspective. Ecological Modelling, 222(1): 176-189.

Key findings and summary for stakeholders

Within the previous research activity of the EUFORIE we stressed the relations between material and energy efficiency as well as aspects of optimization versus maximization of performance parameters, in agreement with Lotka-Odum's Maximum Power Principle, by addressing in particular:
a) the extended meaning of the concept of "cost": not only economic cost, but also resource and environmental costs, to be minimized;
b) the need for a performance optimization strategy (benefits under multiple points of view and for multiple beneficiaries) rather than an efficiency maximization strategy (increase of benefits under one point of view or for one beneficiary only);
c) the possibility to design a tool in support of participatory strategies (involvement of stakeholders in all steps of the decision making process). The tool would ease the evaluation of alternative options and would generate scenarios, in support of policy making.

Concerning the latter point (c), of course "design" does not mean to deliver a fully operating software version of the desired evaluation tool, but instead identifying the criteria, the procedures and the operative features of a tool capable to generate efficiency improvement scenarios. This would allow the implementation of a suitable software for such a tool, with the help of programming experts, if supported by adequate sources of funding. In the present Report we focus on three of the case studies previously investigated and published in refereed Journals, as representative of process, sector and system levels, in order to describe and clarify the suggested rationale and procedure, for future broader implementation. For the sake of simplicity, the present Report aims to provide a clear picture of the potential structure of the tool and its operative modality only based on a limited number of details in each investigated case (focus placed on the tool, not on the actual and final evaluation of the individual cases). Instead, in our final Report we will expand on a more detailed description of the intended tool and its potential results, including a user interface for input of data and an output interface for comparison of results.
We have pointed out many times in past reports and papers that the complexity of technological and economic systems cannot be addressed properly by means of one assessment tool only (e.g. by only evaluation economic costs or energy efficiency) and that a multicriteria and multimethod approach is needed. The intended tool will therefore start by applying an initial set of methods, but remains open to the inclusion of additional evaluation methods when new questions and problems arise. As above stated, for the sake of simplicity we limit the present Report to Life Cycle Assessment (which also includes Cumulative Energy Demand, Land Occupation and a few of specific impact assessment methods), from cradle to grave, and to the Emergy Accounting, which focuses on the relation of the investigated case with inflows of resources and outflows of emissions on the much larger spatial and time scales of biosphere.

In short, these two approachs can be described as follows:
Life Cycle Assessment (LCA) stems from the basic principle that in order to accurately assess the environmental impact of a system or product, all its productive stages must be included in the analysis, “from cradle to grave‘, i.e. from resource extraction to final disposal. Several impacts are evaluated and indicators developed in order to provide a clear picture of resource use and environmental damage generated within a process or an economy. The recently published International Life Cycle Data System (ILCD) Handbook (ILCD, 2010), made available through the European Platform on LCA, further confirms the importance of LCA as a decision-supporting tool in contexts ranging from product development to policy making. The Handbook, a series of technical guidance documents to the ISO 14040-44 standards (ISO 2006a, ISO 2006b), serves as a basis for

comparable and reliable LCA applications in business and public decision-making. Methodologically, a LCA is structured in four consecutive stages, namely: (i) goal and scope definition (including a clear definition of the functional unit, system boundaries and associated assumptions); (ii) life cycle inventory (the compilation of all the inputs and outputs respectively from and to nature associated to all processes that form part of the system's life cycle); (iii) life cycle impact assessment (in which the full inventory of inputs and outputs is translated into a number of aggregated metrics of environmental impact); and (iv) interpretation (in which results are discussed and compared to suitable benchmarks). In all cases, LCA only accounts for matter and energy flows occurring under human control, whereas flows outside of market dynamics (such as environmental services and renewable resources that do not flows through human controlled devices) as well as flows which are not associated to significant matter and energy carriers (such as labor, culture, information) are not generally included. Moreover, the supply-side quality and degree of renewability of resources, in terms of biosphere activity leading to resource generation processes, are not generally taken into account in LCA evaluations. As a consequence, in spite of the very valuable results that an LCA is capable to provide in terms of a process impacts, LCA leaves unaddressed aspects of resource quality in terms of the environmental work for resource generation as well as of environmental support to human-dominated and fully natural systems (value of natural capital and environmental services). This suggests a possible and much needed synergy with the EMergy Accounting approach.

EMergy Accounting (EMA) addresses the environmental work displayed by the past and present work of the Biosphere to generate resources and keep the entire system operating and evolving. In operational terms, emergy is defined as the available energy of one kind (usually solar) previously required, directly and indirectly, to make a service or product. The boundary of the analysis is always set at the biosphere level, thereby keeping track of the entire supply-chain (from resource generation to processing and disposal), and accounting for the environmental support needed to generate all the storages and flows of (renewable and non-renewable) raw natural resources which flow through the web of natural processes supporting the analysed process either directly or indirectly (e.g. in the form of ecosystem services). The unit of emergy is the solar emergy joule (sej), and the emergy to generate one unit of available energy or mass along a particular pathway is named transformity (sej/J) or, more generally, Unit Emergy Value (UEV, seJ/unit). The total emergy driving a system, calculated as the sum of all emergy inflows and also including the emergy investment for disposal or restoration, expresses the environmental cost of the product or service delivered (for further details see the abundant existing literature on the subject). After all the flows of interest have been quantified, a set of additional indicators: Environmental Loading Ratio (ELR), Emergy Yield Ratio (EYR), Emergy Sustainability Index (ESI), among others, can be developed for better understanding of a system's dynamics as well as for environmental policy making (sustainable resource use), by assessing the environmental performance of the process itself. The supply-side and biosphere-scale characteristics of the emergy approach make it capable to assess the demand for environmental support by every natural or human-dominated system or process, in so identifying its reliance on the overall biosphere functioning and interaction with other species and processes. The UEV plays the role of a potential eco-efficiency, in that it allows to compare similarproducts demanding more or less resources for their production and delivery.

The case studies representative of the three levels (process, sector and system) were selected among the ones available in the set of cases investigated and described in our first Report within the framework of the EUFORIE project. The goal is to show how each case is addressed, in order to understand to what extent it contributes to the final performance of the system for which a policy strategy is searched. In other words, the performance of processes producing food, electricity, goods, paper, construction materials, health services, among others, affects the overall performance of the related sectors and converge to determine the final energy, material and environmental performance of the larger scale system of interest (e.g. urban system, regional or national economy, etc). In the present case, for example, the process level focuses on electricity production from conversion and combustion of slaughterhouse animal residues. A preliminary LCA allows to understand which are the input flows that are responsible of the largest impacts in a Business-as-Usual perspective. Once the main inputs are identified, only the largest flow is used as input to the sector and to the system levels and is treated according to three different change patterns (scenarios: 1. Sensitivity assessment based on a given oscillation range representing random and most often unintended fluctuations of resource use; 2. Energy efficiency improvement based on a purposefully applied better technology; and finally, 3. Eco-efficiency improvement based on the replacement of a resource by means of a more environmentally friendly one, according to the emergy approach). These three scenario patterns likely affect both the sector and the system level, since they provide a differently characterized input flow to the upper levels.

A similar computation procedure is then applied to the sector level (in this Report, the production and end-of-life recovery of waste electric and electronic equipment, WEEE) and the same three performance scenarios are computed with impacts transferred to the system level. Of course, as for the process level, the more impacting flows are identified via LCA, but only the largest is transferred to the upper level via the three scenario patterns.

Finally, an LCA of the urban system of Napoli is performed (system level) and the three scenario patterns are applied, also including flows or percentages of flows from the lower levels. In so doing, the performance indicators at system level can be computed as a consequence of (i) selected changes of flows from the lower levels; (ii) assumptions on the extent these changes apply, (iii) solutions based on better technology available; or finally, (iv) environmentally and resource quality driven choices.

While the identification of the more impacting flows is performed via LCA in all the levels, the scenarios for each level are investigated via the emergy accounting method and indicators, capable to provide a very comprehensive environmental picture of the investigated case. Each LCA assessment includes a tentative user interface (to be adjusted in a suitable way when the final tool is created). The Introduction also includes a simulation program that is then applied to each level in order to understand how and how much the assumed input flow changes affect the performance indicators. In the final tool, the changes will apply to all the input flows, while in this Report oscillations apply to selected one or two inflows only.

All in all, energy, matter and eco-efficient choices at the lower levels according to each investigated scenario translate into potential improvement of the larger social and economic system's performance.

The intended goal is to design and make possible a tool for discussion of policies, building on partial tools that we have already created for energy systems (fuel cells) and water-energy-food nexus at urban level. If the tool becomes finally available (perhaps in a following EU funded project, taking advantage of informatic experts), it may be used by policy makers and stakeholders to quickly identify the performance changes generated by technological or environmental choices or simply by more accurate use of resources, capable to affect material and energy efficiency.

Tasks of deliverable 3.1 related to WP3

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.

Tasks of deliverable 3.2, 3.3 and 3.4 related to WP3

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 mean 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

Acronyms and abbreviations

$\%REN = R/U$: Fraction of emergy use that is renewable

BAU: Business As Usual

CC: Climate Change

EC: European Commission

EEI: Eco-Efficiency Implementation

$ELR= (R+N+L+S)/R$: Environmental Loading Ratio

EoL: End of Life

$ESI= EYR/ELR$: Emergy Sustainability Index

$EYR= U/F= (R+N+F+L+S)/F$: Emergy Yield Ratio

F: Emergy flows imported from outside (purchased) or supplied as feedback

FD: Fossil Depletion Potential

FU: Functional Unit

FE: Freshwater Eutrophication

HT: Human Toxicity Potential

ILCD: International Reference Life Cycle Data System Handbook

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

MD: Metal Depletion Potential

N: Locally nonrenewable or slow-renewable emergy flow

POF: Photochemical Oxidant Formation Potential

PV: Photovoltaic

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

TA: Terrestrial Acidification Potential

TE: Terrestrial Eco-Toxicity

TEI: Technology-based Efficiency Improvement

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)

WD: Water Depletion Potential

VBA: Visual Basic for Applications

Energy Units

PJ – Peta Joules (*1015)

TJ – Tera Joules (*1012)

GJ – Giga Joules (*109)

MJ – Mega Joules (*106)

List of tables

List of figures

List of paper published in addition to the ones already included in deliverables 3.1 and 3.2

List of papers submitted and still under review with Acknowledgement to EUFORIE project

Casazza M., Liu G., Mercuri E., Lega M., Ulgiati S., 2018. Under an eco-physics lens: a review of socio-ecological energy constraints and the future of civilization. Submitted to Energy Policy.

Fiorentino G., Zucaro A., Ulgiati S., 2018. Towards an energy efficient chemistry. An assessment of fuel and feedstock switching. Submitted to Energy. Under review.

Vassillo C., Restaino D., Santagata R., Viglia S., Vehmas J., Ulgiati S., 2018. Energy efficiency and stakeholders: Barriers, costs and benefits of implementation. The Naples (Italy) case study case study in the Euforie Project. Submitted to Journal of Environmental Accounting. Under review.

Santagata R., Viglia S., Fiorentino, G., Liu G.Y, Ripa, M., 2018. Power generation from slaughterhouse waste materials. An Emergy Accounting assessment. Submitted to Journal of Cleaner Production. Under review.

Rallo, R.F., and Zucaro, A., 2018. Assessing the energy metabolism of urban systems: A comparison of Naples and Hong Kong via the MuSIASEM approach. Submitted to the Journal of Environmental Accounting and Management. Under review.

List of papers accepted with Acknowledgement to EUFORIE project

Huang S., An H., Fang W., Viglia S., Fiorentino G., Corcelli F., Ulgiati S., 2017. Terrestrial transport modalities in China concerning monetary, energy and environmental costs. Energy Policy. Accepted for publication.

Mehmeti, A., McPhail, S., Ulgiati, S., 2018. Fuel cell eco-efficiency calculator (FCEC): A simulation tool for the environmental and economic performance of high-temperature fuel cells. Energy. Accepted for publication.

Xue, J.Y., Liu, G.Y., Casazza, M., Ulgiati, S., 2018. Development of an Urban FEW nexus online analyzer to support urban circular economy strategy planning. Submitted to Energy. Accepted.

Assessment of costs and benefits of energy efficiency solutions.

List of papers published with Acknowledgement to EUFORIE project

Corcelli F., Ripa M., Ulgiati S., 2018. Efficiency and sustainability indicators for papermaking from virgin pulp – An emergy-based case study. Resour. Conserv. Recycl. 131, 313–328. doi:10.1016/j.resconrec.2017.11.028

Ghisellini P., Ripa M., Ulgiati S., 2018. Exploring environmental and economic costs and bene fits of a circular economy approach to the construction and demolition sector. A literature review. J. Clean. Prod. 178, 618–643. doi:10.1016/j.jclepro.2017.11.207

Corcelli, F., Fiorentino, G., Vehmas, J., Ulgiati, S., 2018. Energy efficiency and environmental assessment of papermaking from chemical pulp - A Finland case study. J. Clean. Prod. 198, 96–111. doi:10.1016/j.jclepro.2018.07.018

Santagata, R., Ripa, M., Ulgiati, S., 2017. An environmental assessment of electricity production from slaughterhouse residues. Linking urban, industrial and waste management systems. Appl. Energy 186, 175–188. https://doi.org/10.1016/j.apenergy.2016.07.073

Corcelli, F., Ripa, M., Leccisi, E., Cigolotti, V., Fiandra, V., Graditi, G., Sannino, L., Tammaro, M., Ulgiati, S., 2016. Sustainable urban electricity supply chain – Indicators of material recovery and energy savings from crystalline silicon photovoltaic panels end-of-life. Ecol. Indic. doi:10.1016/j.ecolind.2016.03.028

Corcelli, F., Ripa, M., Ulgiati, S., 2017. End-of-life treatment of crystalline silicon photovoltaic panels. An emergy-based case study. J. Clean. Prod., 161, pp. 1129-1142 https://doi.org/10.1016/j.jclepro.2017.05.031.

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Chapter 1. Introduction

The aim of deliverable D.3.3 is to address the following expected impacts, previously identified in the project proposal:

- One high quality summary information package concerning organizational tools for energy efficiency
- One summary report about product and process innovation towards energy efficiency (including ideas and basic knowledge for internal R&D for energy efficiency)
- One hardware report of energy efficiency (Knowledge brokerage information of capital good useable for energy efficiency (facilities, machines, tools, identified best practices).

In order to meet the above points, this deliverable presents a preliminary version (rationale, partial simulation program, case examples) of a Prototype Tool suggested as a useful support to the stakeholders and policy makers discussion and decision processes. Integration of LCA (Life Cycle Assessment) and EMA (EMergy Accounting) methods was carried out in the Prototype Tool and early results suggesting improved energy and material efficiency procedures are shown at different levels (Process, Sector and System level, as schematized in the project proposal). The final version of the Prototype Tool will be presented in the deliverable D 3.4 in response to the Task 3.6. As mentioned in earlier deliverables and Partner Meetings, the Prototype tool is not to be intended as a ready-to-use online tool, since the transfer of rationale and theoretical schematization to even a beta version of a usable tool requires much more resource investment and informatic expertise that were not available in the EUFORIE project Consortium and budget. However, Deliverable 3.4 will design a roadmap to achieve such a result, if believed important at EU level.

The development of the Prototype Tool addresses the Task 3.5 whereas the part of the deliverable related to the MuSIASEM approach completes the Tasks 3.4, afterwards the Deliverable 3.2. Due to lack of suitable statistical data about time series for all investigated case studies (D 3.1), the application of ASA-LINDA model was not possible. The inclusion of MuSIASEM and ASA additional features can be made following the same procedure described here for LCA and EMA and would enrich the tool by means of additional abilities to disaggregate data, identify constraints and make scenarios.

According to the project proposal, three different levels were investigated in the same geographical framework in a way that the process and sector level could be consistently integrated within the system level. The case studies were selected from deliverable D 3.1. In particular, the animal by-products case study was investigated at process level, the photovoltaic end of life case study at sector level and the Naples urban case study at system level. In Figure 1 the interconnections among electricity production from animal waste, recovery of WEEE (Waste Electric and Electronic Equipment, e.g. phovoltaic panels, computers) and urban system are highlighted within a circular economy perspective: the savings in the production of electricity compared to the conventional route as well as the energy savings linked to the recovery of materials from WEEE translate into a better sustainability performance of the whole urban system.

The development of the prototype is aimed at merging the knowledge of LCA and EMA frameworks for synergic results. The LCA represents a standardized method providing qualitative, quantitative, confirmable and manageable environmental performance of the investigated processes or products, as defined by ISO standards and ILCD Handbook guidelines (ISO 14040, 2006; ISO 14044, 2006; EC, 2010; EC, 2011). EMA integrates renewable sources, resource generation time, trade flows, resource quality aspects, labor and services in the LCA approach. Further details on the used methodologies are reported in deliverable D 3.1.

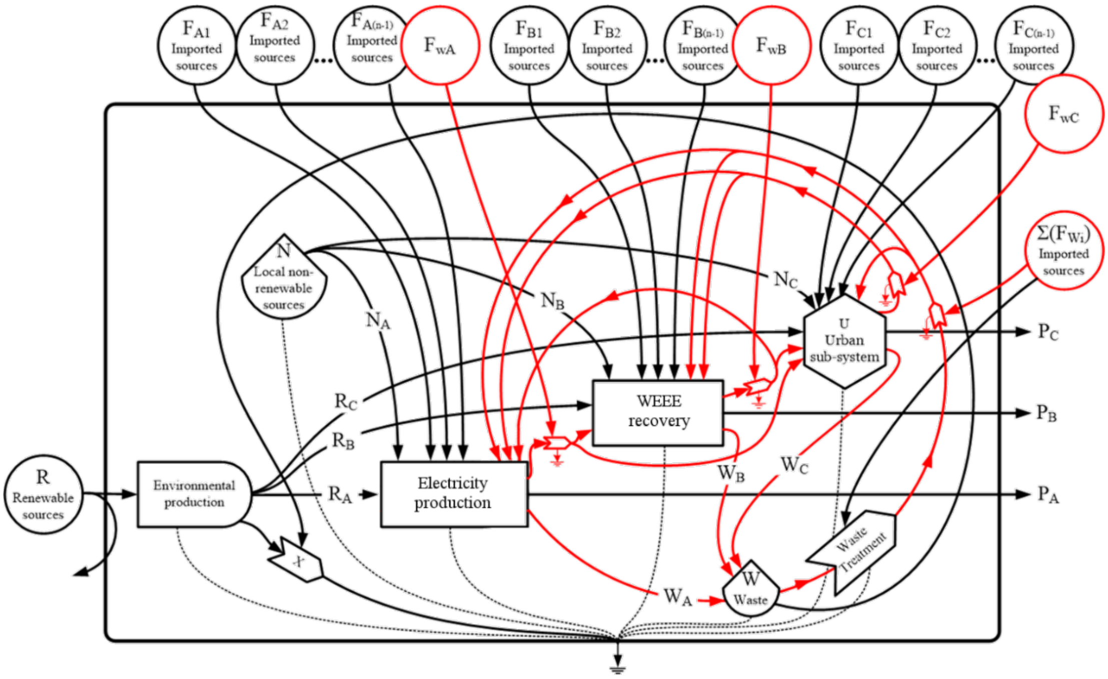

Figure 1 – System diagram of the integrated circular urban system. It shows the interconnections between the different levels presented in a circular framework.

The tool was developed to enable the evaluation of the performance of 3 scenarios at different levels:

1. Improved Business As Usual (I-BAU) scenarios, evaluating the system as it is (with focus on the sensitivity of results to uncertainty of input and output data, in order to better understand the system's behavior and impacts before any decision is made. Also best practices already well accepted and implemented are included as I-BAU);
2. Technology-based Efficiency Improvement (TEI), to suggest improvements of the investigated level through energy and material efficiency, according to the LCA approach (e.g., by considering a reduction of the main energy and material input flows through technological innovation, such as improved management, design, thermal insulation, light emission diode-LED technology, all of which not yet sufficiently adopted as best practices);
3. Eco-Efficiency Implementation (EEI), i.e. achievable improvements of the environmental sustainability by substituting energy and material hotspots with renewable or less environmental costly input flows according to the EMA approach.

Technology-based Efficiency Improvement and Eco-efficiency are applied separately to each level or even together to detect the potential for further improvement. A general assumption is made about the output generated: we assume that the amount of electricity and heat generated as output does not change, i.e. the same product is obtained thanks to appropriate management (I-BAU), technological innovation (TEI), and quality increasing (EEI) variations of input flows. In order to compare on the same basis the results of the three scenarios, the emergy performance indicators (total U and $UEV_{product}$) are compared. Of course, a likewise comparison would be impossible if the I-BAU scenario were assessed in energy terms, the TEI in LCA terms and the EEI in EMA terms.

The final version of the prototype tool is thought to be developed for supporting participatory processes at different levels starting from previous attempts carried out for the performance evaluation of energy systems (Bargigli et al., 2010; Zucaro et al., 2013; Mehmeti et al., 2018) and urban systems (Casazza et al., 2017; Xue et al., 2018) within the EUFORIE research team at Parthenope,and also as a follow up of previous national and EU research projects, by taking advantage of the large network of collaboration links of Parthenope with other research groups worldwide. In this Deliverable, an Excel spreadsheet was implemented for the three selected case studies and the results show the interlinkages among levels and methods. The influences of the performance at process level may be envisaged at the sector level, which in turn has consequences on the system level. For instance, in this deliverable, the sustainable end of life of the photovoltaic panels (material efficiency) improves the overall energy efficiency at urban level; the valorization of animal waste to produce power sources (energy efficiency within a circular economy framework) produces a double benefit, by reducing wastes to be disposed of (material efficiency and recovery) and by generating renewable electricity and heat (energy recovery).

The main goal of the developed tool is to identify hotspots and propose potential energy and material efficiency improvement patterns as policy actions. A user interface with inputs and corresponding variability percentages (uncertainty) was designed and linked to the LCA and EMA calculation procedure worksheets in order to identify the main input flows affecting the environmental performance of the investigated scenario and to implement the above-mentioned improvements for the hotspots. The uncertainty level related to each input can differently influence the final outcome of the developed scenarios (e.g. a highly impacting input characterized by low variability may affect the results more than another input with higher variability but minor relevance in producing environmental loads). For this reason, the focus was placed on the input flows identified in the I-BAU scenarios as the most impacting in the LCA and EMA approach. Consequently, these inputs were subjected to energy and material improvements according to the above scenarios Technology-based Efficiency Improvement and Eco-efficiency. For instance, if electricity results to be the main hotspot of the evaluated environmental performance of the I-BAU scenario, the user can insert a percentage range of variation related to the input of electricity (related to uncertainty in the Scenario 1, to achievable technological efficiency in Scenario 2, to Eco-Efficiency factors derived from the EMA approach in Scenario 3), and the tool, by means of a macro coded in VBA (Visual Basic for Application language), will compute 200 random values within that range, updating the various indicators and plotting them into graphs. For each case study, the three different scenarios were therefore built. The details of proposed improvements are described in the following Sections. For each case study, in the I-BAU scenario three major hotspot are identified in order to apply the sensitivity oscillations. In the other scenarios, the improvement hypotheses are only applied to the major hotspot, for the sake of simplicity and comprehensiveness.

Table 1 – VBA code for the creation of 200 random values within a range. The same code is applied to three different inputs for the variation in every scenario.

Range(Cells(10, 11), Cells(65536, 11)).ClearContents	To clear the cells where results will be shown.
	Variable a equal to value of input flow
a = Cells(7, 11).Value	Variable b equal to minimum of variation range
b = Cells(7, 12).Value	Variable c equal to maximum of variation range
c = Cells(7, 13).Value	Random value variable
r = 0	Loop counting variable
t = 0	Start printing results from row 10
i = 10	
	Beginning of randomization function
Randomize	
	To obtain 200 different values
Do Until t > 200	
	r is equal to a random value between the
r = WorksheetFunction.RandBetween(b, c)	minimum and the maximum of the range
	Random value to percentage
r = r / 100	Random value printed
Cells(i, 12) = r	
	Value of input flow times the random
Cells(i, 11) = a + (a * r)	percentage and printed
	Counter increase by 1
t = t + 1	Move to next row
i = i + 1	
	Loop for 200 times
Loop	

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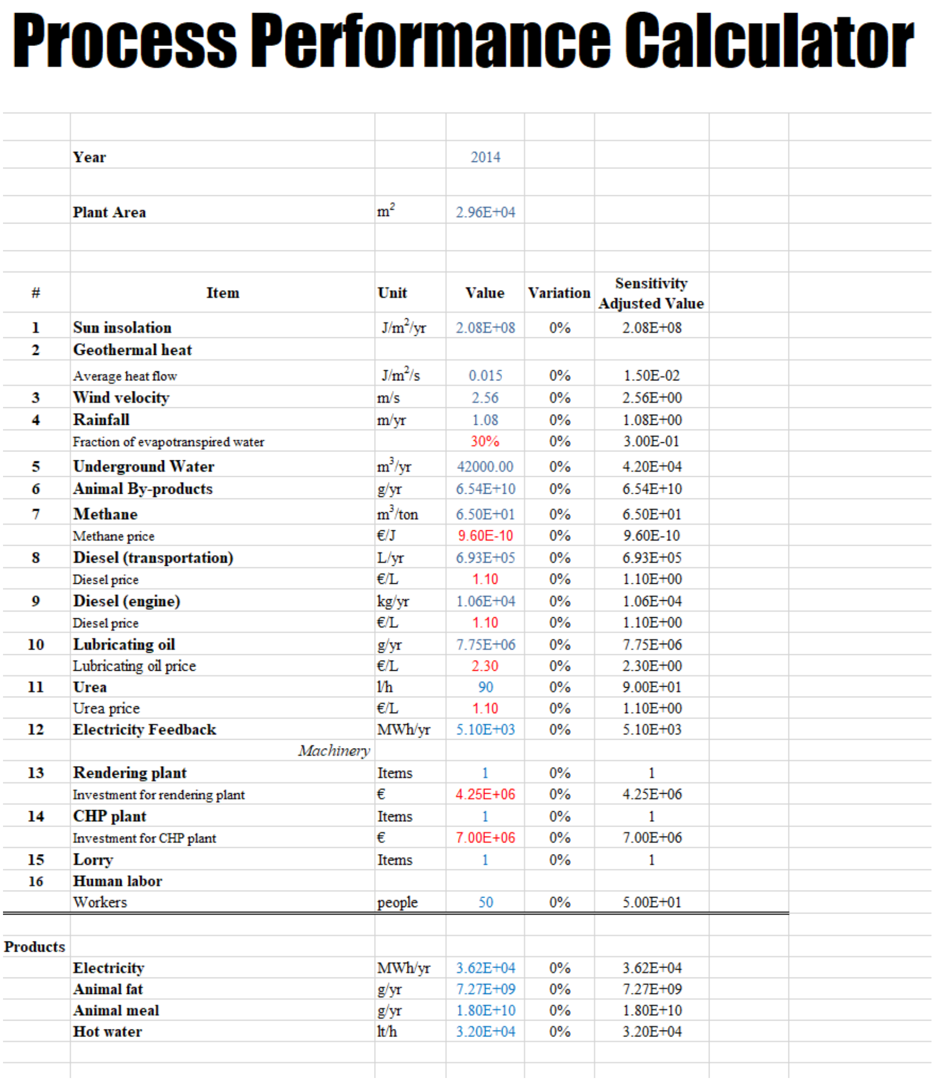
Chapter 2 – Process level. Electricity generation from Animal Waste

The food processing industry continues to grow, generating large amounts of organically rich waste flows per year: these processors face significant economic and environmental pressures for appropriate conversion and disposal of these waste flows. Therefore, the addressing of waste conversion processes is crucial in order to: i) reduce waste disposal problems, ii) improve the environmental performance of investigated processes through energy and material efficiency and iii) suggest the implementation of added-value products to be integrated in a broader system level. In order to fulfill the aim developed in this deliverable, the recycle of animal waste in Campania region has been selected as process level case study.

2.1. The process. Description and operation (Life Cycle Assessment)

The investigated process is characterized by the collection and the processing of animal by-products to produce electric energy and other useful co-products. The animal material undergoes a rendering process to obtain a protein-rich fraction converted in animal meal and a fat fraction partially used as fuel in a cogeneration power plant to produce electricity (average 5.1 MW) and heat. The investigated process is operated by Proteg S.P.A., a company located in the industrial area of the municipality of Caivano (Naples), in Campania region, Italy (detailed description of the investigated system reported in Santagata et al., 2017, work carried out within the framework of EUFORIE project). The evaluation of the environmental performance of the process has been carried out by means of the spreadsheet prototype tool “Process Performance Calculator” (Figure 2), merging LCA and Emergy method. As mentioned earlier in this Deliverable, this tool allows to: i) evaluate the process environmental sustainability; ii) measure the process environmental profitability through several LCA/emergy-based indicators and their variation; iii) provide information and support to policy makers and other stakeholders involved in decision making. The tool allows the user to insert all the relevant input flows for the assessment, delivering a set of performance indicators and graphs, for support to discussion and policy. The User Interface presented in Figure 2 allows the user to enter the relevant data (inventory of input and product flows) expressed with the needed units and then adjust the uncertainty percentage according to known and unknown characteristics of each flow, in order to perform a sensitivity assessment.



Process Performance Calculator

	Year		2014
	Plant Area	m^2	2.96E+04

#	Item	Unit	Value	Variation	Sensitivity Adjusted Value
1	**Sun insolation**	$J/m^2/yr$	2.08E+08	0%	2.08E+08
2	**Geothermal heat**				
	Average heat flow	$J/m^2/s$	0.015	0%	1.50E-02
3	**Wind velocity**	m/s	2.56	0%	2.56E+00
4	**Rainfall**	m/yr	1.08	0%	1.08E+00
	Fraction of evapotranspired water		30%	0%	3.00E-01
5	**Underground Water**	m^3/yr	42000.00	0%	4.20E+04
6	**Animal By-products**	g/yr	6.54E+10	0%	6.54E+10
7	**Methane**	m^3/ton	6.50E+01	0%	6.50E+01
	Methane price	€/J	9.60E-10	0%	9.60E-10
8	**Diesel (transportation)**	L/yr	6.93E+05	0%	6.93E+05
	Diesel price	€/L	1.10	0%	1.10E+00
9	**Diesel (engine)**	kg/yr	1.06E+04	0%	1.06E+04
	Diesel price	€/L	1.10	0%	1.10E+00
10	**Lubricating oil**	g/yr	7.75E+06	0%	7.75E+06
	Lubricating oil price	€/L	2.30	0%	2.30E+00
11	**Urea**	l/h	90	0%	9.00E+01
	Urea price	€/L	1.10	0%	1.10E+00
12	**Electricity Feedback**	MWh/yr	5.10E+03	0%	5.10E+03
	Machinery				
13	**Rendering plant**	Items	1	0%	1
	Investment for rendering plant	€	4.25E+06	0%	4.25E+06
14	**CHP plant**	Items	1	0%	1
	Investment for CHP plant	€	7.00E+06	0%	7.00E+06
15	**Lorry**	Items	1	0%	1
16	**Human labor**				
	Workers	people	50	0%	5.00E+01
Products					
	Electricity	MWh/yr	3.62E+04	0%	3.62E+04
	Animal fat	g/yr	7.27E+09	0%	7.27E+09
	Animal meal	g/yr	1.80E+10	0%	1.80E+10
	Hot water	lt/h	3.20E+04	0%	3.20E+04

Figure 2 – User interface for Process level LCA/Emergy Inventory. Animal waste recovery case study (input flows are highlighted in blue and economic values of input flows are highlighted in red).

According to the standardized LCA procedure, the impact assessment of the process level was performed by means of SimaPro 8.0.5.13 software coupled with the ReCiPe Midpoint (H) v.1.12. In this study, the following LCA impact categories are explored: Global Warming Potential (CC, in kg CO_2 eq), Human Toxicity Potential (HT, in kg 1,4-DB eq), Fossil Depletion Potential (FD, in kg oil eq), Metal Depletion Potential (MD, in kg Fe eq), Water Depletion Potential (WD, in m^3), Freshwater Eutrophication Potential (FE, in kg P eq), Terrestrial Acidification Potential (TA, in kg SO_2 eq), Terrestrial Ecotoxicity Potential (TE, kg 1,4-DB eq), Photochemical Oxidant Formation Potential (POF, in kg NMVOC).

The animal waste recovery case study is considered a ‘gate to gate’ approach, since the physical boundaries of the plant are coincident with the investigated system boundaries (Figure 3).

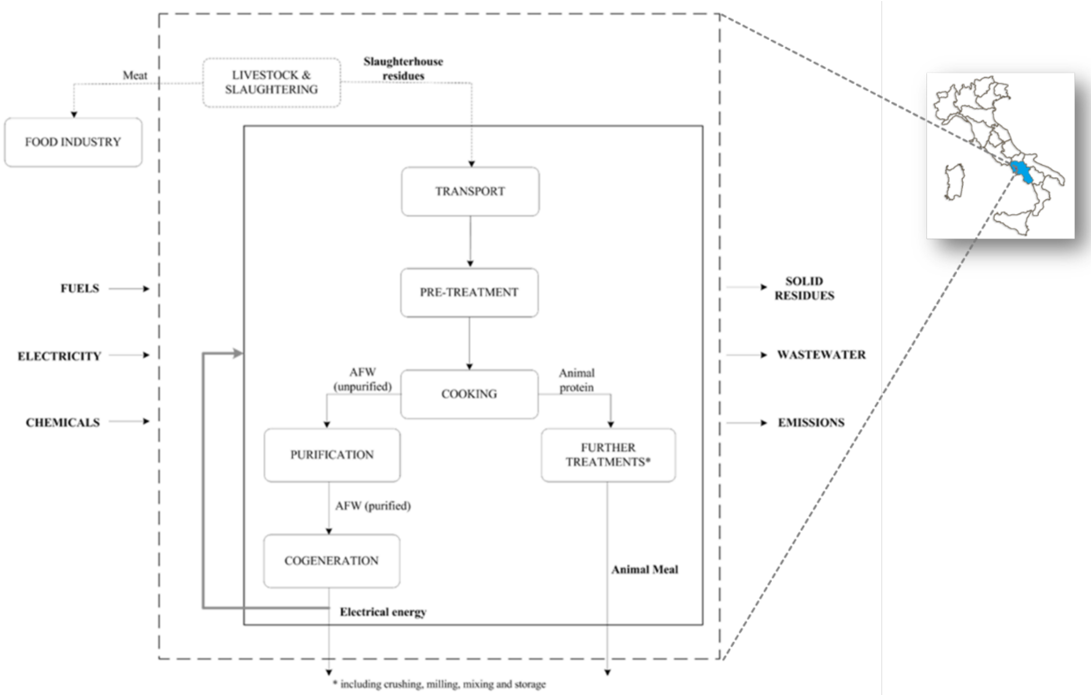


Figure 3 –System boundary of the animal waste recovery case study (process level).

The functional unit selected for the study is 1 MWh of electricity generated. An accurate inventory of all the input and output flows was carried out considering 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 (Figure 3). The entire process can be divided into two sub-processes: (1) Rendering process of the organic material, yielding meal and fat fractions; (2) Generation of electric energy via the combustion of animal fat (Figure 4). All input flows and environmental burdens are allocated to the meal and fat exiting the first phase as coproducts, according to their mass; then, the fraction of inflows and outflows allocated to fat is assigned to the electricity generated in the second phase. According to a practice very common in LCA, a ‘zero-burden waste’ approach is assumed in this study, by not including the burdens associated to the upstream generation of treated waste (Bala Gala et al., 2015). This is why our Figures do not include the agricultural and livestock farm levels.

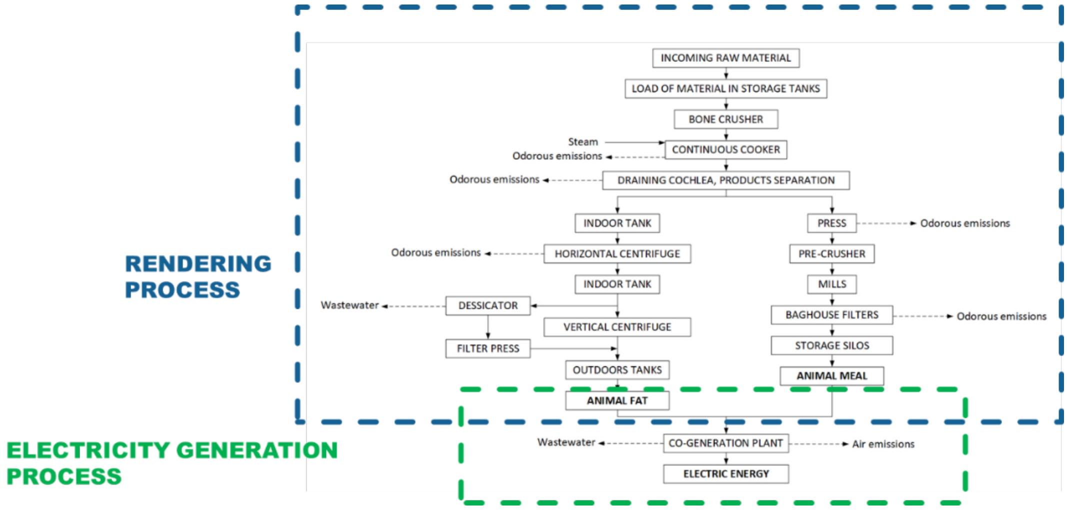
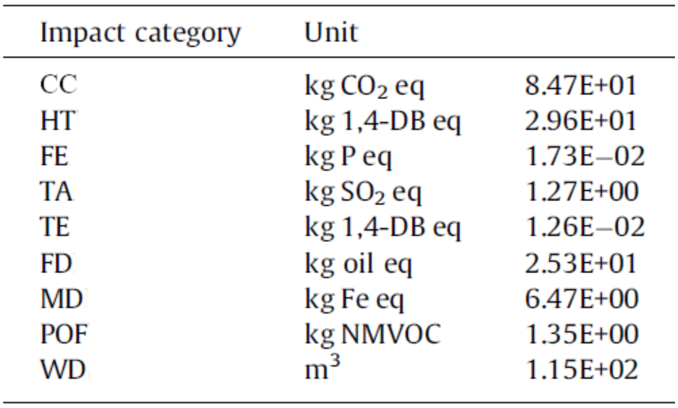


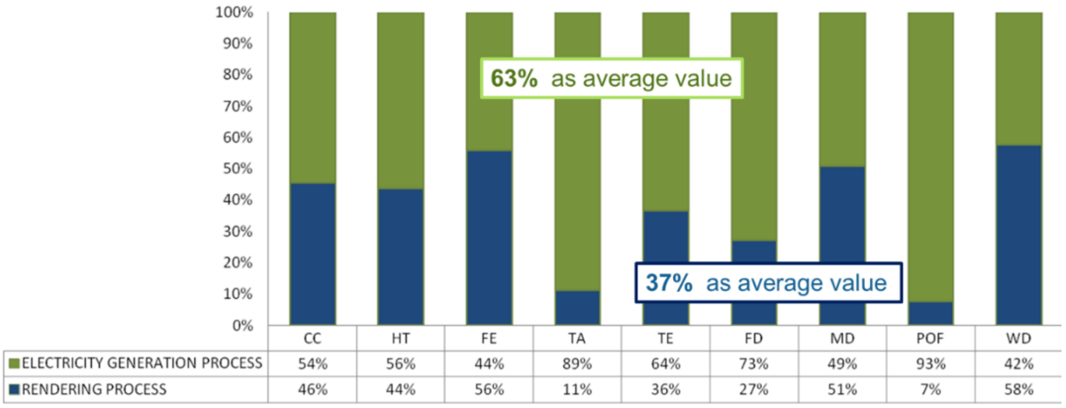
Figure 4 – Animal waste recovery case study description.

The LCA results are shown in Table 2. Figure 5 shows the different share of the two production steps, highlighting the relevance of the electricity generation process.

Table 2 – Characterized impacts calculated for the generation of 1 MWh of electric energy from animal by-products



Impact category	Unit	
CC	kg CO_2 eq	8.47E+01
HT	kg 1,4-DB eq	2.96E+01
FE	kg P eq	1.73E–02
TA	kg SO_2 eq	1.27E+00
TE	kg 1,4-DB eq	1.26E–02
FD	kg oil eq	2.53E+01
MD	kg Fe eq	6.47E+00
POF	kg NMVOC	1.35E+00
WD	m^3	1.15E+02



	CC	HT	FE	TA	TE	FD	MD	POF	WD
🟩 ELECTRICITY GENERATION PROCESS	54%	56%	44%	89%	64%	73%	49%	93%	42%
🟦 RENDERING PROCESS	46%	44%	56%	11%	36%	27%	51%	7%	58%

Figure 5 – The characterization graph shows the relative contribution of the two sub-processes to the total burdens of energy from animal waste recovery.

Total burdens of each production phase are shown in the characterization diagram (Figure 6) highlighting the contribution of the different input flows to the total burdens. The urea input flow, used for the selective reduction of NO_x emissions in the electricity generation phase, is the largest contributor to almost all impact categories, followed by the methane, used for steam generation in the rendering process, and by the diesel used for the collection of animal waste (transportation).

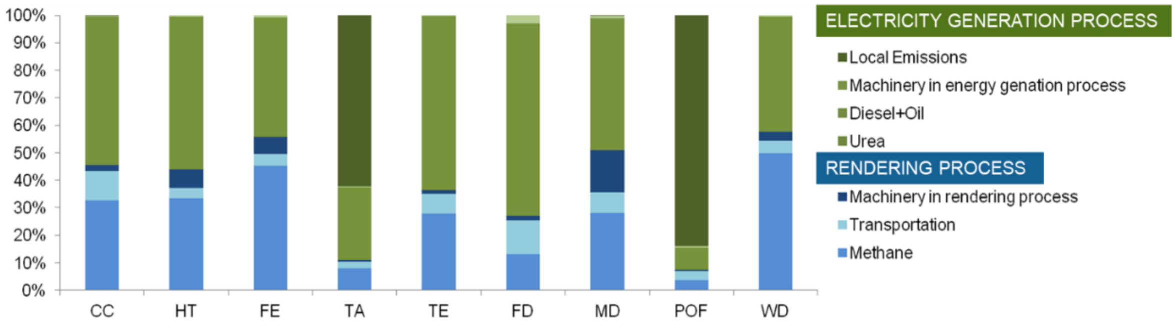
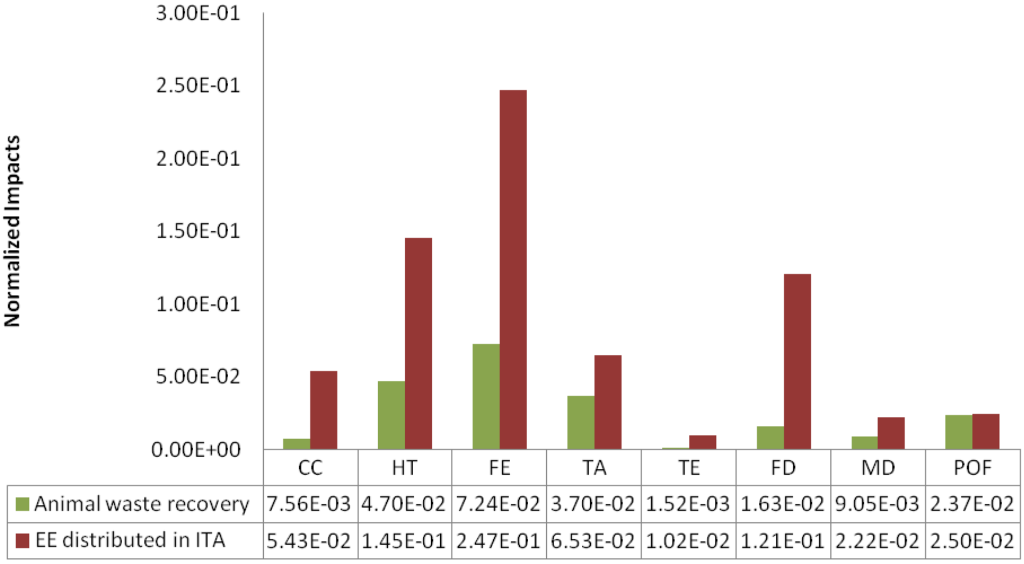


Figure 6 – Characterization graph shows the relative contribution of the two main stages to the total burdens of energy from animal waste recovery.

The main goal of this case study was the evaluation of the profitability of using animal by-products to produce electricity together with other commodities (i.e. animal meal, purified fat, heat). For this reason, in order to gain an understanding of the suitability of such electricity generation process, a comparison with the impacts of the Italian electric mix (national grid) 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 animal by-products is much lower than those associated with the Italian mix, 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 by the investigated waste management process are around one order of magnitude smaller than those generated by the Italian electricity mix. Figure 7 shows the normalized impacts of the comparison between the two energy supply chain.



	CC	HT	FE	TA	TE	FD	MD	POF
🟩 Animal waste recovery	7.56E-03	4.70E-02	7.24E-02	3.70E-02	1.52E-03	1.63E-02	9.05E-03	2.37E-02
🟥 EE distributed in 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 7 – Normalized impacts comparing the Electricity (EE) production from animal waste and the Italian electricity production (mix of fossil fuels and renewables).

From the LCA perspective, the main hotspots are the use of methane, urea and diesel for transportation, nevertheless the impacts generated by the electricity production from animal by-products results to be more environmentally sustainable than the average Italian electricity mix under a I-BAU + zero burden LCA perspective. In order to reach a technology base efficiency improvement and eco-efficiency implementation, the LCA point of view was integrated within the scheme of the prototype tool by means of reduction of selected inflows due to more efficient use and replacement of selected inflows weighted via EMA ecosystem and socio-economic parameters (so called UEVs, Unit Emergy Values, a measure of environmental quality of resources).

2.2. Scenarios of the assessment at process level

The process level has been therefore analyzed exploring three different scenarios:

- Scenario 1 - Improved Business as Usual (I-BAU): evaluating the system as it is, considering a statistical variation for relevant hotspot input flows, in order to explore sensitivity to data errors, uncertainty, unavailability.
- Scenario 2 - Technology-based Efficiency Improvement (TEI): considering a reduction of selected (more impacting items) energy and material input flows through technological improvement (better management, design, cohibentation, led).
- Scenario 3 - Eco-efficiency Implementation (EEI): improving the environmental sustainability of the system level through substitution of energy and material hotspots with renewable or less environmental costly input flows.

Scenario 1 - Improved Business as Usual (I-BAU)

The first scenario (sensitivity oriented) was developed considering a variation in the main impacting energy and material input flows considering a range of -10% and 10%. For the animal waste recovery case study, the selected hotspots are methane, urea and diesel for collection. The identification of hotspots was made based on the LCA breakdown of impacts shown in Figure 6.

Figure 8 shows the assumed variation in the methane input flow, in a range within -10% and +10%, applied to an input of 4.20E+09 J/MWh declared by the Company. The resulting minimum is 3.78E+09 J/MWh, while the maximum is 4.62E+09 J/MWh.

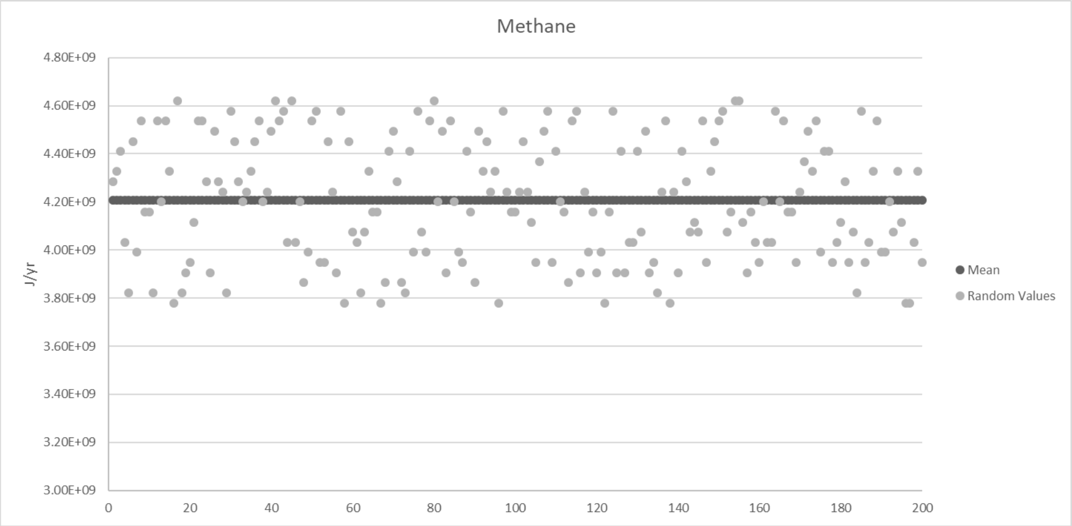


Figure 8 – Improved Business as Usual scenario: Methane input flow variation within a range of -10% and +10%

The -10%/+10% variation applied to the Urea input flows of 2.37E+04 g/MWh, gave back the same quantity as mean value, with a minimum of 2.13E+04 g/MWh and a maximum of 2.61E+04 g/MWh (Figure 9).

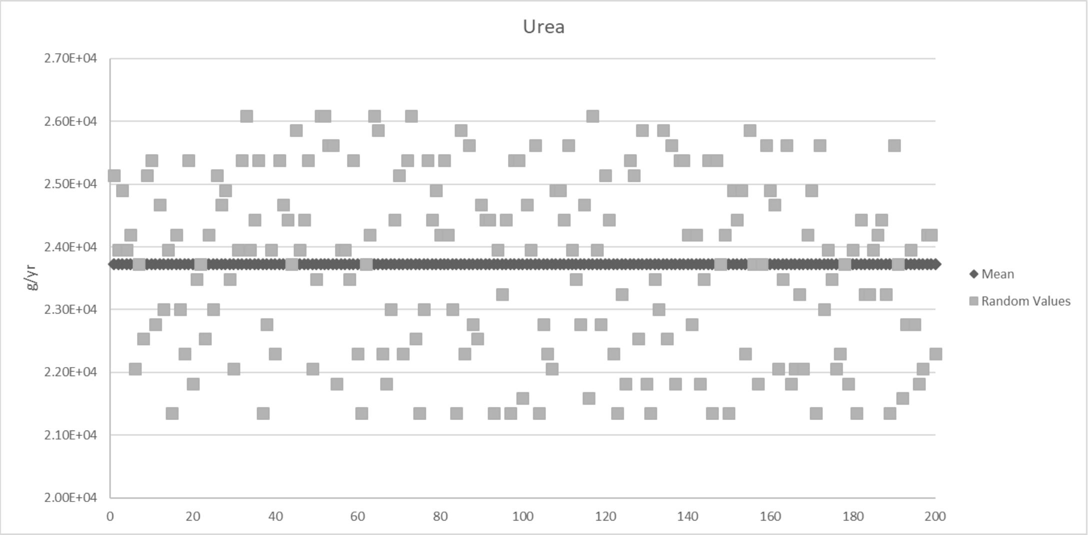


Figure 9 – Improved Business as Usual scenario: Urea input flow variation within a range of -10% and +10%

The same variation for the diesel input caused a mean value of 7.04E+08 J/MWh, over a raw input of 7.04E+08 J/MWh, with a minimum of 6.37E+08 J/MWh, and a maximum of 7.79E+08 J/MWh (Figure 10).

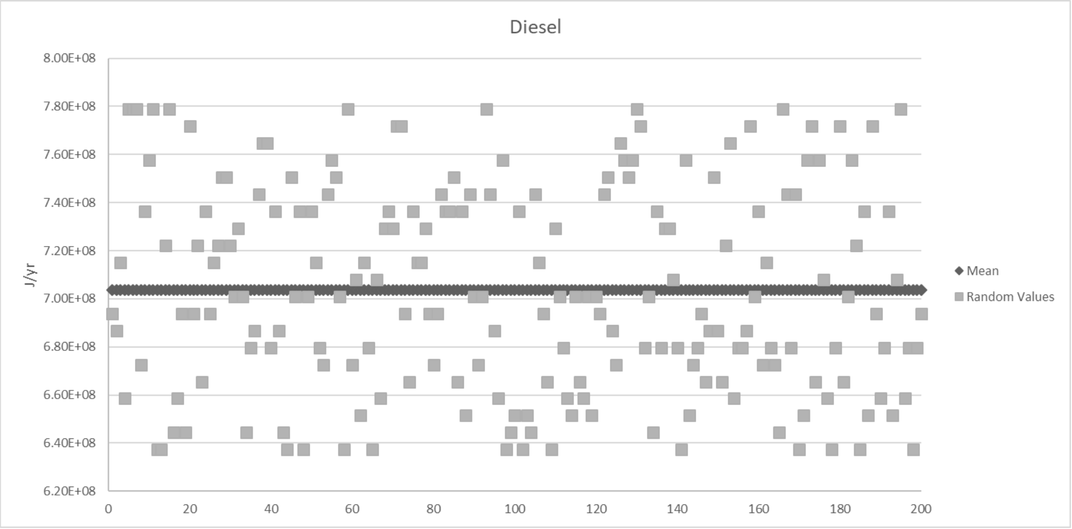


Figure 10 – Improved Business as Usual scenario: Diesel input flow variation within a range of -10% and +10%

The total emergy U associated to 1 MWh of electricity produced, U_{FU} (FU= Functional Unit), will vary together with the variation of input flows. It shows the environmental loading in terms of use of renewable local input emergy flows, imported non-renewable emergy flows, and non-renewable local emergy flows (Figure 11 and Figure 12). U_{FU} has been calculated considering the accounting of Labor and Services (L&S) in Figure 11 and without L&S in Figure 12. Without taking into account the sensitivity oscillations, U_{FU} with L&S shows a mean value of 1.02E+15 sej/MWh, while U_{FU} without L&S is equal to 8.33E+14 sej/MWh. The minimum value of U_{FU} with L&S is 9.41E+14 sej/MWh, 8% less than the mean value; the maximum value is 1.09E+15 sej/MWh, 7% more. The minimum value of U_{FU} without L&S is 7.58E+14 sej/MWh (-9%), the maximum is 9.09E+14 sej/MWh (+9%).

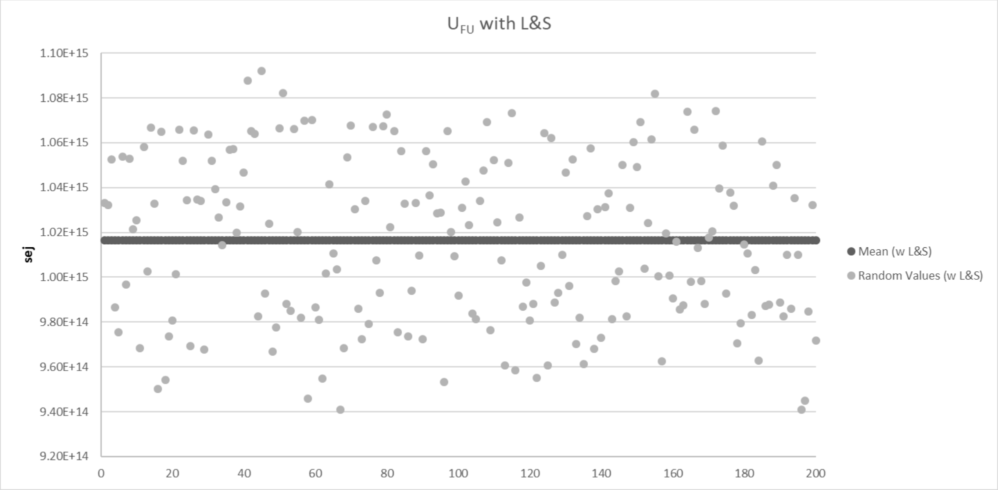


Figure 11 – Improved Business as Usual scenario: Variation of U_{FU} with L&S

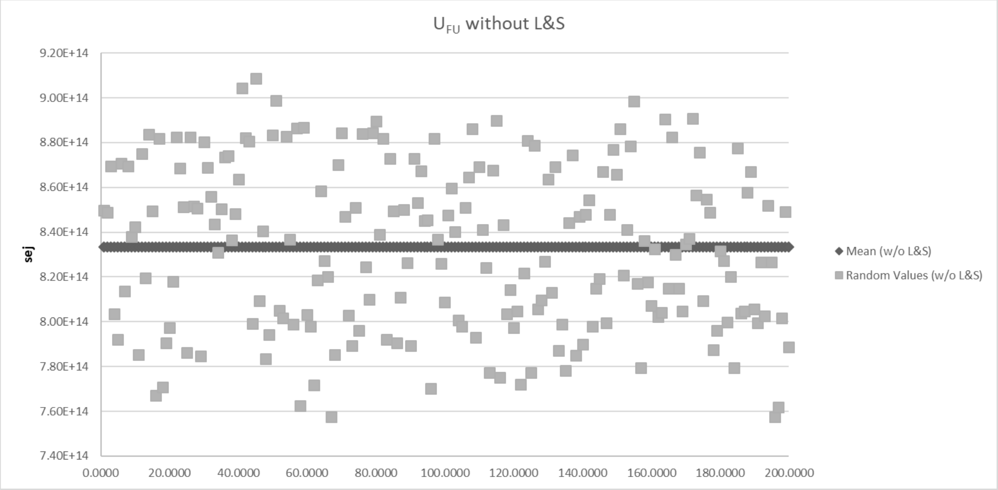


Figure 12 – Improved Business as Usual scenario: Variation of U_{FU} with L&S

Figure 13 shows the comparison between U_{FU} with and without L&S in order to show the importance of the inclusion of L&S in the evaluation. The added value in the use of EMA is the possibility to include in the analysis the burden related to L&S. In the EMA approach, the L&S value becomes a measure of the indirect environmental cost of infrastructures, information and know-how.

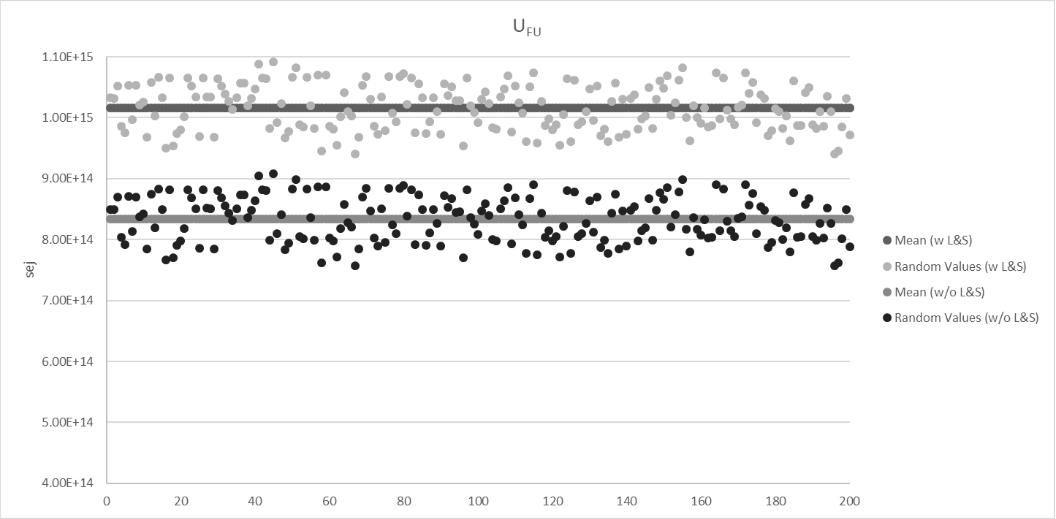


Figure 13 – Improved Business as Usual scenario: **–** Total emergy U_{FU} with and without L&S

In addition to the total emergy U_{FU}, at the process level, the UEV (Unit Emergy Value) of the electricity produced was computed. Although the two intensive indicators are strictly related, the first one was computed in order to facilitate the comparison with LCA-based values, while the second one was computed in order to facilitate the comparison with emergy-based values, both from our published papers and from other Authors. A similar computation is performed in the following of this report, for the sector and system levels. The $UEV_{electricity/L\&S}$ with L&S is equal to 3.29E+05 sej/J, while without L&S it is equal to 2.69E+05 sej/J. Introducing the sensitivity oscillations, the $UEV_{electricity/L\&S}$ oscillates within a minimum of 3.04E+05 sej/J (-7.6%) and a maximum of 3.53E+05 sej/J (+7.3%). $UEV_{electricity}$ without L&S, oscillates between a minimum of 2.45E+05 sej/J (-8.9%) and a maximum of 2.94E+05 sej/J (+9.3%). Figure 13 shows both variations.

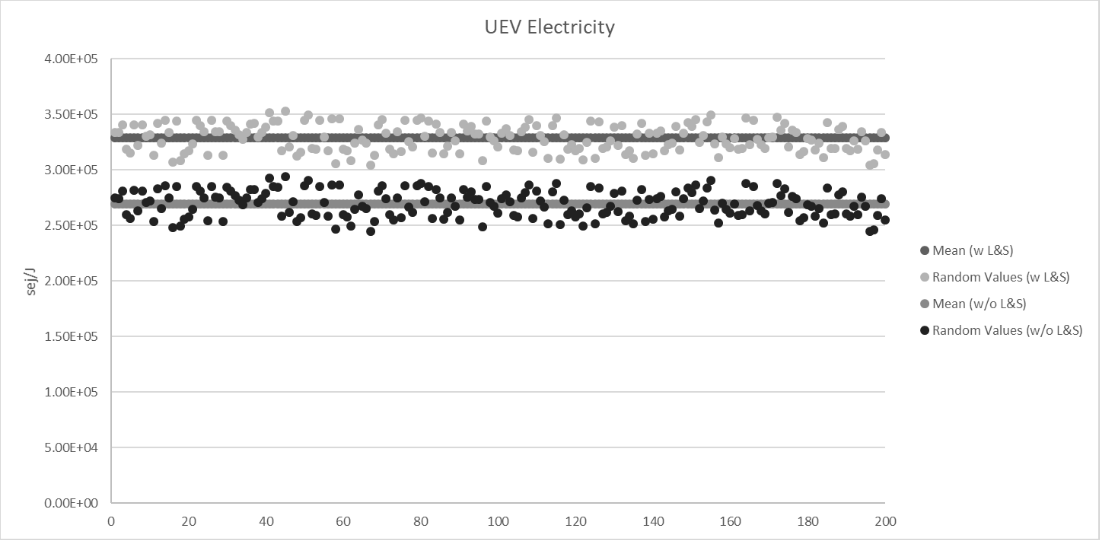


Figure 14 – Improved Business as Usual scenario: sensitivity of UEVs of electricity from animal by-products with and without L&S, to assumptions of fluctuating values of selected inflows.

Scenario n. 2 - Technology-based Efficiency Improvement (TEI)

In the TEI scenario a better use of the main resource inflows contributing to the environmental burdens was assumed and benefits quantified. We focused on the methane inflow, decreased in the range of -20% and 0%, under the assumption of increased use efficiency (i.e. assuming the use of a high efficiency burner).

The imposed reduction of the methane input flow between -20% and 0% is simulated in Figure 15. The assumed reduction generates a methane input flow around a mean value of 3.77e+09 J/MWh (instead of the I-BAU 4.20E+09 J/MWh), with a minimum of 3.36E+09 J/MWh, and an obvious maximum of 4.20E+09 J/MWh.

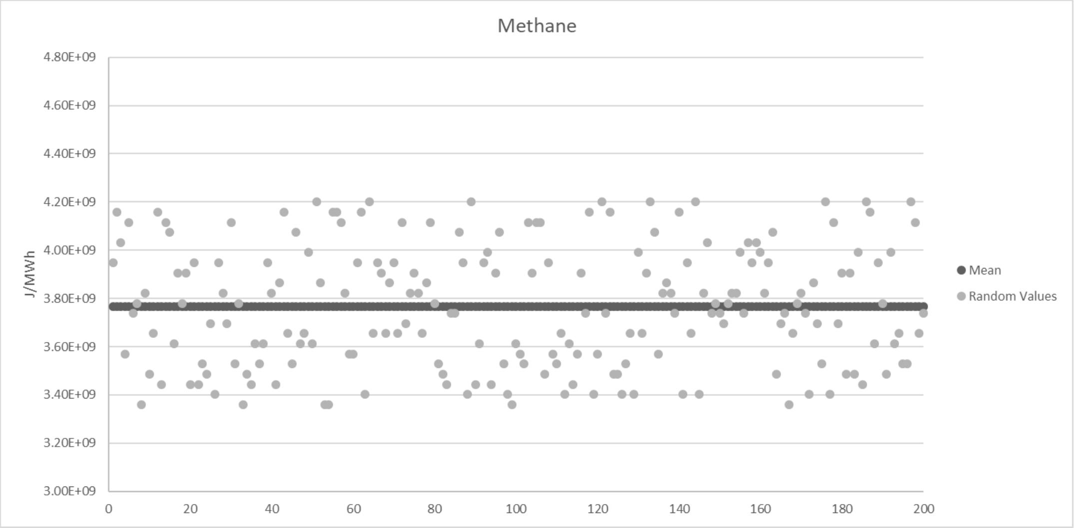


Figure 15 – Technology-based Efficiency Improvement scenario: Improvement of hotspot flow.

The methane-focused TEI translates into U_{FU} mean values of 9.55E+14 sej/MWh with L&S and 7.72E+14 sej/MWh without L&S (Figure 16), respectively -6.4% and -7.3% compared to the I-BAU scenario. UEV of electricity mean value with L&S is 3.09E+05 sej/J, without L&S is 2.50E+05 sej/J (Figure 17).

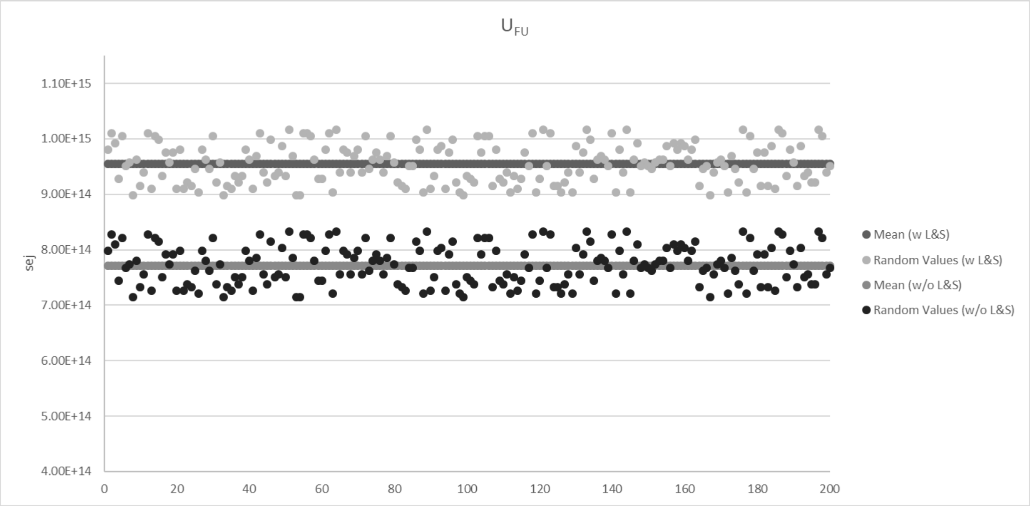


Figure 16 – Technology-based Efficiency Improvement scenario: Total emergy U_{FU} with and without L&S.

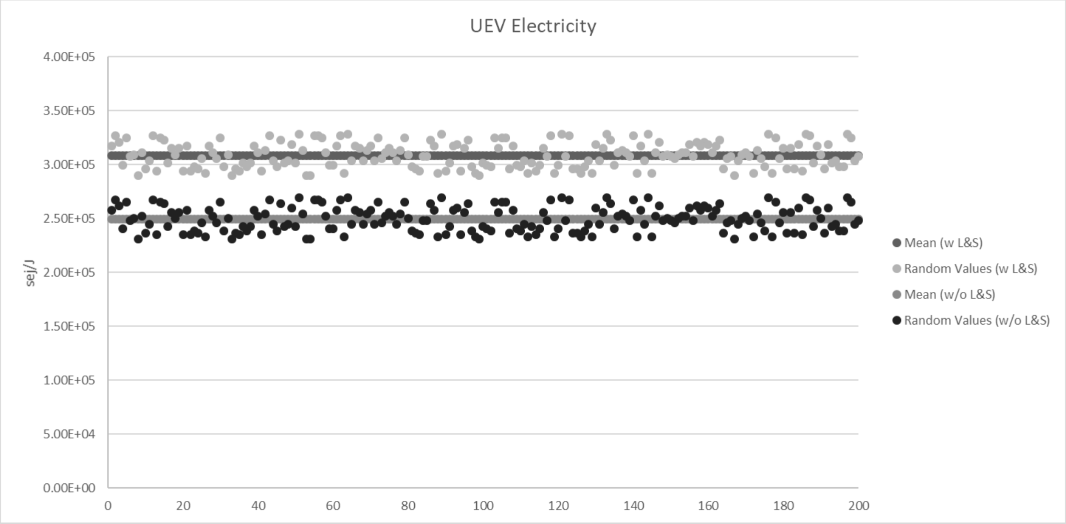


Figure 17 – Technology-based Efficiency Improvement scenario: UEV of electricity from animal by-products with and without L&S.

Scenario n. 3. Eco-Efficiency Implementation (EEI)

The variation in the third scenario (Eco-Efficiency) was related to the increased quality of selected hotspot input flows. The methane supporting the investigated process system was replaced by bio-methane produced from organic waste (Wang et al, 2014), with a variation range between -10% and 10%. Biomethane is characterized by a much lower UEV (eco-efficiency).

The related total emergy U_{FU} shows values of 6.67E+14 sej/MWh and 4.83E+14 sej/MWh respectively with and without L&S (Figure 18), further improving both I-BAU and TEI scenarios. Electricity UEVs calculated under the Eco-Efficiency scenario show values of 2.16E+05 sej/J with L&S and 1.56E+05 sej/J without L&S (Figure 19), about 40% lower than the TEI scenario.

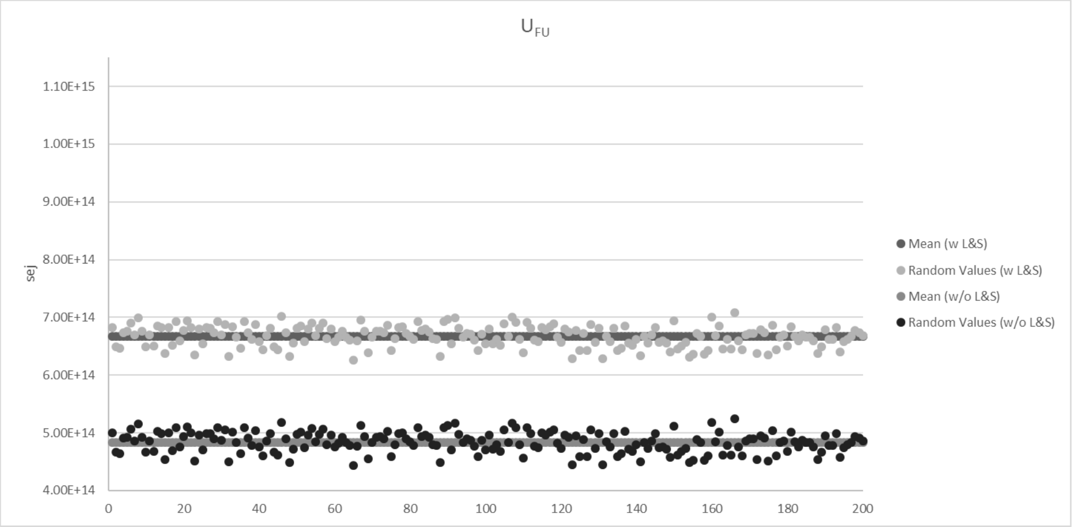


Figure 18 – Eco-Efficiency scenario: Total Emergy U_{FU} with and without L&S

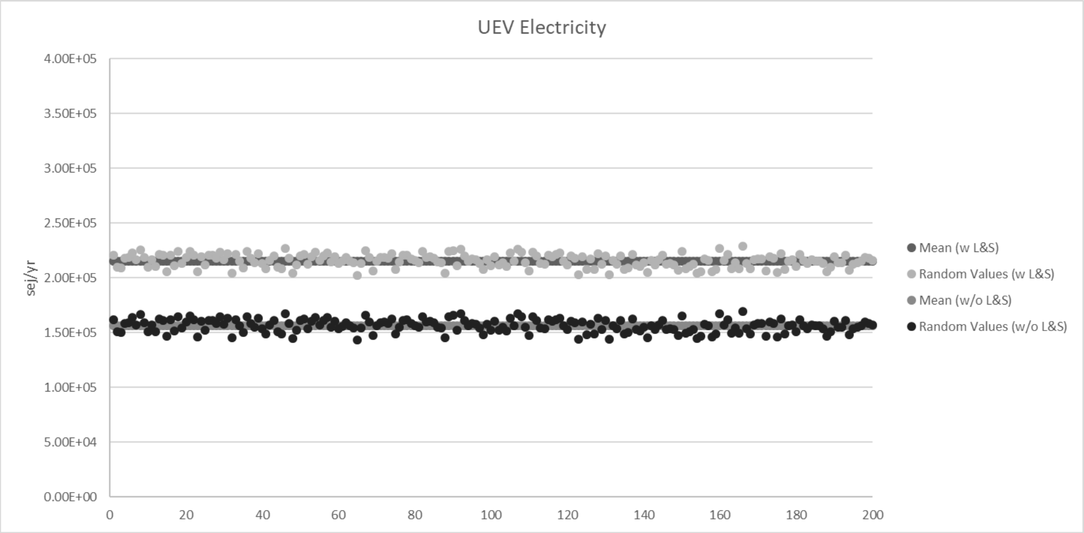


Figure 19 – Eco-Efficiency scenario: UEV of electricity from animal by-products with and without L&S.

2.3. Emergy Assessment of process at power plant level

Finally, a total emergy assessment was also computed (Santagata et al., 2018) with regard to the total annual net production of electricity (U_{PLANT}). U_{PLANT} in the I-BAU scenario is equal to 3.02E+19 sej (without L&S) and 3.68E+19 sej (with L&S). Computing the total U_{PLANT} provides an estimate of the "environmental size" of the plant in terms of its demand for environmental support, to be compared to the total emergy supporting the economy of the City of Naples (Viglia et al, 2017) or any larger area of interest (i.e. region or nation), in a likewise manner. This measure, equal to 0.3% with L&S and 0.4% without L&S, complements similar comparisons made in monetary terms (e.g. when economic analyses state that the value of the annual product of a plant is a given % of the total regional GDP) or other measures such as Ecological Footprint.

2.4. A circular economy framework

The scenario analysis developed thanks to this early prototype tool provides recommendations and suggestions to improve the environmental feasibility of the investigated process level. Through the three investigated scenarios, the reduction of the main hotspot (methane) due to the Technology-based Efficiency Improvement scenario, TEI, although showing better results than the I-BAU case, results to be less sustainable than its complete substitution by a more eco-friendly fuel (Eco-Efficiency Implementation scenario, EEI). Results quantify and underline both the extent of achievable improvements under TEI and EEI assumptions. The "quantify" must be underlined: stakeholders and policy makers must be able to move from rethoric to actual implementation, by means of effective resource use planning, only possible if quantitative assessment of the consequences can be provided.

This study at process level was performed keeping in mind an idea of circularity. 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. This is expected to make better use of the available resources, to allow increased wellbeing at no or low environmental costs, i.e. the implementation of a system in which products are created in a perspective of use and reuse, disassembling and recycling, gaining resources from ‘waste’ materials, minimizing the extraction of new raw materials. Obviously, animals are not bred to produce electricity. The results of this study should not be intended as the proposal for an electricity production process, but instead as a way of increasing the sustainability of the larger scale process through material and energy loops, reusing the by-products generated by the meat industry, retrieving the residual value of something destined otherwise to be managed as ‘waste’, and finally providing a link between the production phase (primarily rural) and the consumers (primarily urban).

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Chapter 3. Sector level – 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. 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% 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. 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.

3.1. WEEE recovery. From process to sector level.

The recovery of end-of-life (EoL) photovoltaic (PV) panels, an example of material efficiency within urban system, was selected in order to move the attention from the process level to the **sector level**. PV 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, 2015), and the related end of life (EoL) environmental issues, European Union calls for a long-term sustainability of the PV industry. Indeed, decommissioned PV panels are included, for the first time, in the list of WEEE in the EU Directive 2012/19/EC.

PVs are not the only typology of WEEE (Waste Electric and Electronic Equipment). In a few years, the photovoltaic waste materials will provide a huge contribution to the WEEE sector, namely the collection and treatment of all kinds of residues from electric and electronic industry (PV, smart phones, desk and laptop computers, internet cloud technologies, refrigerators, air conditioner, electronic devices of vehicles, as well as all the expected devices presently in development course and known as "intelligent house/domotics"). This growing sector is going to create huge environmental problems. The latter are not, however, only a matter of environmental impact, but also an issue of increased energy demand (just think of the industrial production of electronic grade silicon materials and components or the demand of electricity for temperature stabilization of big servers and computer centres). The PV production and recovery as well as the computer production and recovery have been investigated within the EUFORIE project as typical processes referring to the much larger sector of modern electronic devices. Improvements in production and recovery technologies of these devices will immediately translate into environmental benefits as well as material and energy efficiency improvements at the regional and national sector level, especially in consideration of the strategic importance of several minerals that are at the basis of these kind of technological devices.

3.2. The investigated electric and electronic sector

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). Appropriate EoL management of PVs may offer a sustainable solution to resource availability, economic feasibility and EoL related environmental risks (Choi and Fthenakis, 2014). 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 recovery of PV panels.

The investigated PV panel recovery process 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) (detailed description of the investigated system is reported in Corcelli et al., 2016, 2017, works carried out in the framework of EUFORIE project).

Typically, PV crystalline silicon (c-Si) panels are made with the following components, listed in order of increasing mass: glass (~75%), aluminium frame (~10%), copolymer encapsulant (~7%, e.g. EVA, ethylene-vinyl-acetate, PVB, poly-vinyl-butyral or TPO, thermoplastic polyolefine elastomer), protective back sheet (~4%, e.g. PVF, polyvinyl-fluoride, or glass), photovoltaic cells (~3%), junction box and electrical contacts (~1%). The recovery of a PV panel involves technically complex steps but would provide recovered materials for the electronic industry. Generally, the recovery process begins with the disassembly of the aluminium frame and junction box, frequently done manually, followed by the removal of the EVA layer, in order to separate the glass from the silicon cells. The most common method used to decompose the EVA layer is the thermal treatment (Allen et al., 2000).

After removing the aluminum frame and the junction box, a 10 cm x10 cm sample was cut by means of a circular saw; it was placed inside a furnace in the presence of a stream of air, then heated from ambient temperature until 600°C, keeping it at this temperature for 30 min. The final temperature and the duration of the test have been decided in order to ensure that the thermally degradable parts of the panel were fully degraded (i.e. PVF and EVA decompose around 450 °C and 350°C, respectively). The electric furnace used for thermal treatment is manufactured by Borel Swiss company, and it has 14 kW power (further details at: https://www.borelfurnaces.com/standard_furnaces_ovens/printable/products/furnaces-500-1300c/industrial-furnaces-550-c/index.html).

The outputs of the investigated thermal treatment 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.

3.2.1. The LCA scenarios and results

The LCA impact assessment of the process level was performed by means of SimaPro 8.0.4.30 software coupled with the ReCiPe Midpoint (H) v.1.10. In this study, the following impact categories are explored: Climate Change (CC, in kg CO_2 eq), Photochemical Oxidant Formation (POF, in kg NMVOC), Terrestrial Acidification (TA, in kg SO_2 eq), Freshwater Eutrophication (FE, in kg P eq), Terrestrial Ecotoxicity (TE, kg 1,4-DB eq), Human Toxicity (HT, in kg 1,4-DB eq), Water Depletion (WD, in m^3), Metal Depletion (MD, in kg Fe eq), Fossil Depletion (FD, in kg oil eq).

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 (Figure 20a), 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 aluminium – 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;
- a **low-rate (LR)** recovery scenario (Figure 20b): only the aluminium 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.

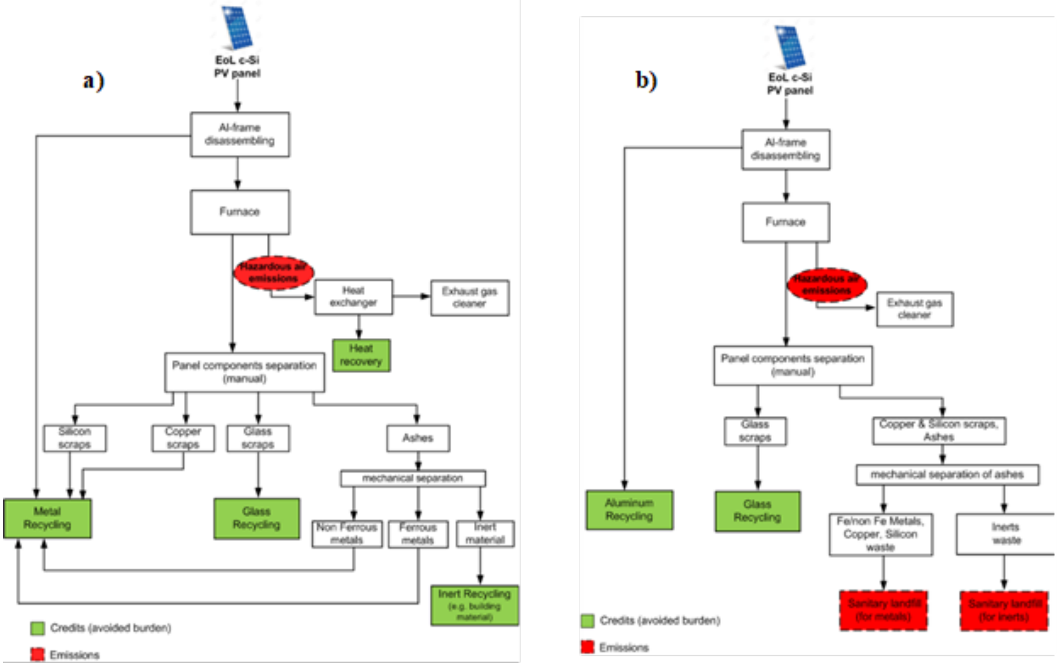


Figure 10 – a) Flow chart of high-rate recovery scenario (HR); b) Flow chart of low-rate recovery scenario (LR).

In this case study the environmental impacts are analyzed with reference to 1 m^2 of PV panel treated (functional unit, FU). As very common in LCA, a 'zero-burden waste' approach is assumed in this study, by not including the burdens associated to the upstream generation of treated waste (Bala Gala et al., 2015).

The abovementioned goals of the study are achieved with special attention to the following objectives:

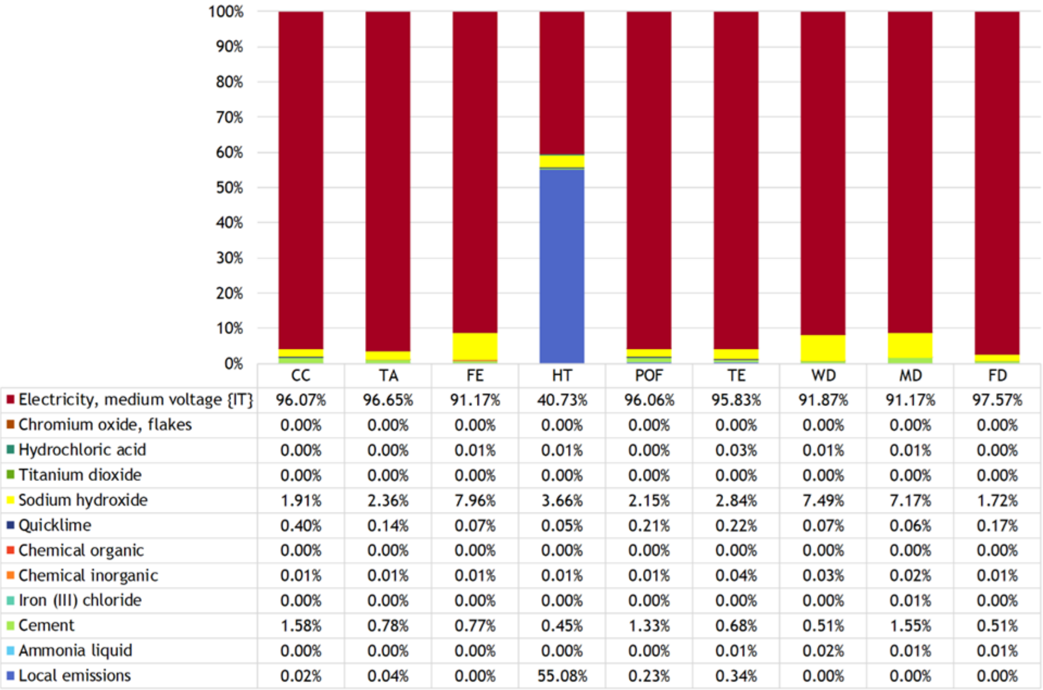
(1) to identify the flow(s) or steps that are most "responsible" of the environmental impacts in the PV panel thermal treatment and resources' recovery;

(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 (i.e. heat, glass and metals recovered) 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 (see Table 4 and Figure 22 below), they indicate that savings in the production of virgin metals and heat by conventional routes are allowed and environmental benefits are attained.
The LCA characterized results are shown in Table 3. Total burdens of the thermal treatment process are shown in the characterization diagram (Figure 21) highlighting the contribution of the different input flows to the total burdens. The Italian electricity mix input flow, used as only source of energy for the thermal treatment phase, is the largest contributor to almost all impact categories (91-98%, red color in Figure 21), followed by sodium hydroxide (2-8%) used for the exhaust gas treatment.

Table 3 – Characterized impacts calculated for the thermal treatment of 1 m^2 of PV panel treated (functional unit).

Impact category	Unit	Value
CC	kg CO_2 eq	1.22E+00
TA	kg SO_2 eq	4.71E-03
FE	kg P eq	2.07E-04
HT	kg 1,4-DB eq	4.24E-01
POF	kg NMVOC	2.82E-03
TE	kg 1,4-DB eq	7.93E-05
WD	m^3	8.79E-03
MD	kg Fe eq	3.24E-02
FD	kg oil eq	3.70E-01



	CC	TA	FE	HT	POF	TE	WD	MD	FD
■ Electricity, medium voltage {IT}	96.07%	96.65%	91.17%	40.73%	96.06%	95.83%	91.87%	91.17%	97.57%
■ Chromium oxide, flakes	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
■ Hydrochloric acid	0.00%	0.00%	0.01%	0.01%	0.00%	0.03%	0.01%	0.01%	0.00%
■ Titanium dioxide	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
■ Sodium hydroxide	1.91%	2.36%	7.96%	3.66%	2.15%	2.84%	7.49%	7.17%	1.72%
■ Quicklime	0.40%	0.14%	0.07%	0.05%	0.21%	0.22%	0.07%	0.06%	0.17%
■ Chemical organic	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
■ Chemical inorganic	0.01%	0.01%	0.01%	0.01%	0.01%	0.04%	0.03%	0.02%	0.01%
■ Iron (III) chloride	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.00%
■ Cement	1.58%	0.78%	0.77%	0.45%	1.33%	0.68%	0.51%	1.55%	0.51%
■ Ammonia liquid	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.02%	0.01%	0.01%
■ Local emissions	0.02%	0.04%	0.00%	55.08%	0.23%	0.34%	0.00%	0.00%	0.00%

Figure 21 – Characterization graph shows the relative contribution of each inputs to the thermal treatment recovery process.

Figure 22 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 POF and MD categories, 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 analysed categories, ranging from a minimum of 56% in HT to a maximum of 80% in FE. Beyond silicon recovery, the second main contribution to environmental benefits comes from the recovery of aluminium in all impact categories, except for TE and MD. It is worth to point out that silicon and aluminium recovery are the main responsible of the negative values, equalling together more than 70% of the total avoided impact in all categories. In particular, FE and CC are the indicators where the avoided (i.e. negative) burden given by silicon and aluminium reaches 99% and 96%, respectively. Overall, a positive performance also in the LR scenario, thanks to the recovery of glass and aluminium is noticeable. In particular, the environmental benefits of the aluminium recovery are achieved in all analysed categories, with values ranging from a minimum of 78% in TE to a maximum of 92% in FE. 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 MD and FD categories, the disposal phase contributes to the impact with a share of 20% approximately.

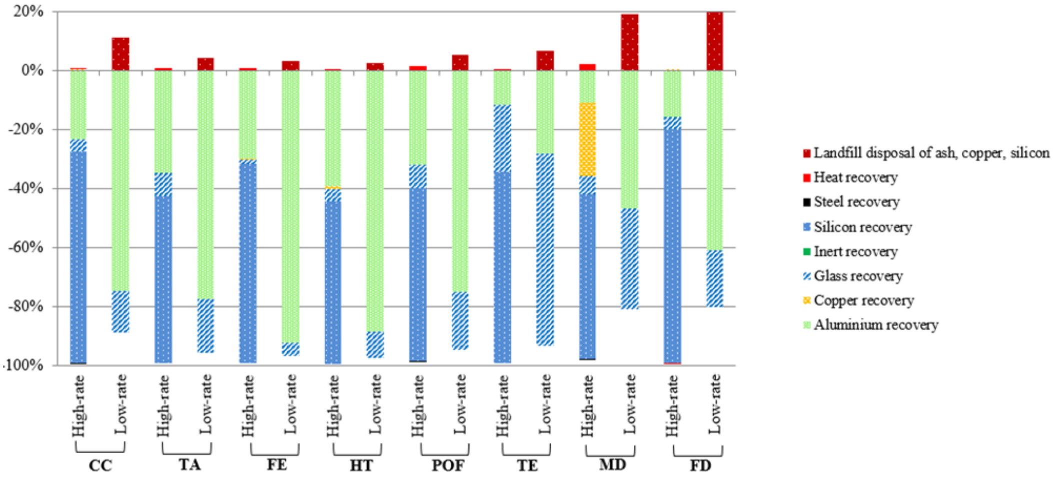


Figure 22 – Contributions to normalized impacts from each single phase of high-rate and low-rate scenarios (WD category is not detectable due to the normalization factor equal to zero and it is not shown).

Table 4 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. All the resulting values are negative, meaning that both scenarios turn out to be favourable (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 CC, HT and FD categories.

Table 4 – Characterized impacts calculated for the high-rate and low-rate scenarios, referred to a functional unit of 1 m^2 PV panel treated (negative values correspond to environmental avoided impacts thanks to energy and material recovery).

Impact category	Unit	HR	LR
CC	kg CO_2 eq	-8.69E+01	-1.92E+01
TA	kg SO_2 eq	-5.79E-01	-2.29E-01
FE	kg P eq	-4.39E-02	-1.31E-02
HT	kg 1,4-DB eq	-4.18E+01	-1.73E+01
POF	kg NMVOC	-2.98E-01	-1.10E-01
TE	kg 1,4-DB eq	-7.61E-03	-2.32E-03
WD	m^3	-2.14E+00	-5.06E-01
MD	kg Fe eq	-2.04E+00	-2.39E-01
FD	kg oil eq	-2.06E+01	-2.64E+00

When focus is placed on understanding the actual impacts of the thermal treatment or recovery process, it is important to look at the process performance separate from the advantages provided by the recovered products, in order to avoid the risk that the latter hide the former. From the LCA perspective, it was observed that the main hotspot of PV panel thermal treatment was the use of electricity, and only a minor contribution came from sodium hydroxide, used for effluent gas treatment.

3.3. Scenarios of the assessment at sector level

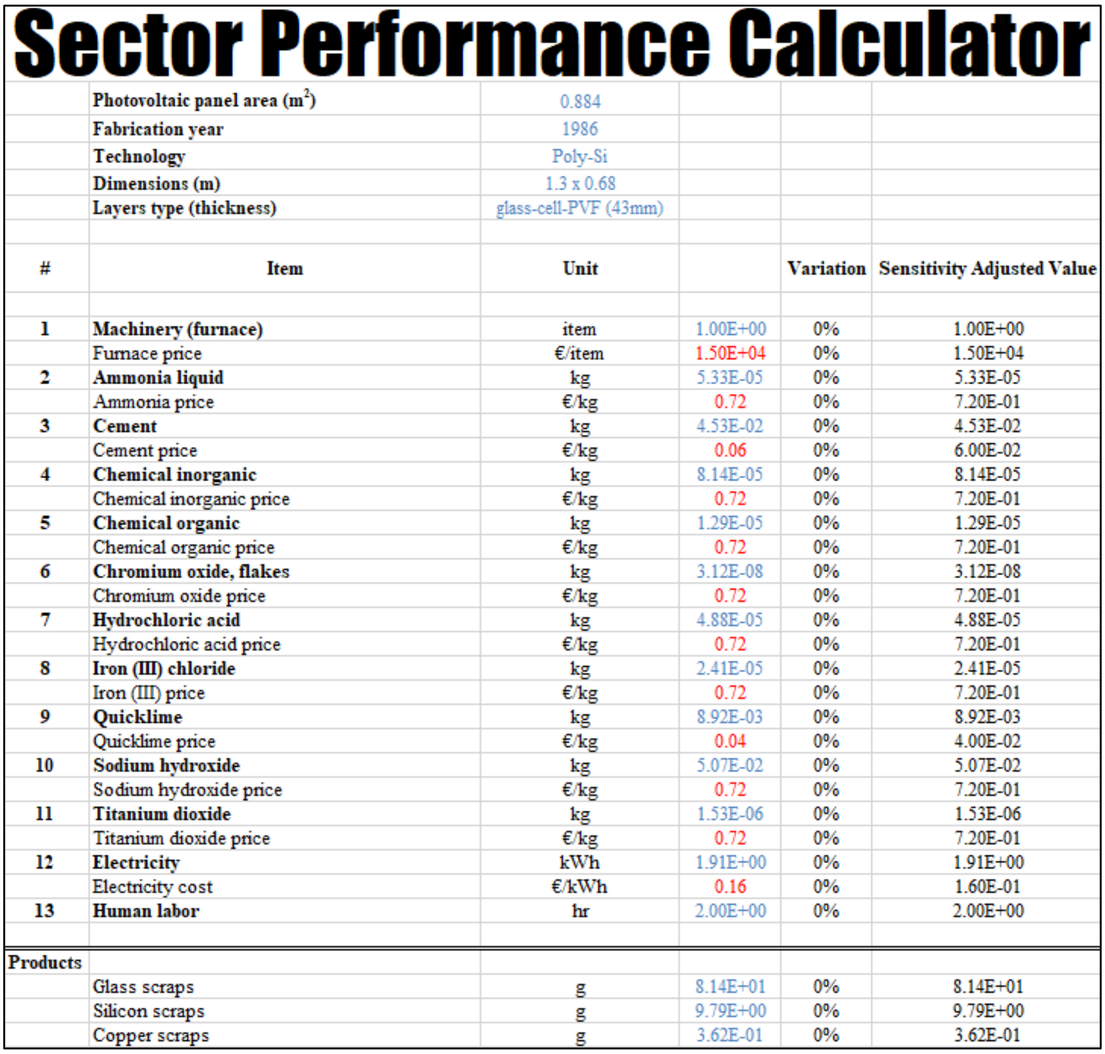
The research team has investigated the production and recycling of two kinds of electronic devices, PV modules and obsolete computers, as representative of the entire electronic industry and WEEE recovery sectors. Clearly, the WEEE directive of the European Union includes other typologies, but the goals of this prototype tool is not to provide a complete picture of all options available, but to show how data from the process level investigation can be transferred and expanded to the sector level, namely in this case from specific process cases to the WEEE recovery sector. In order to evaluate the WEEE environmental performance and recovery potential at sector level, the spreadsheet prototype tool “Sector Performance Calculator” was applied to achieve the following goals:

i) evaluate the environmental sustainability of a crystalline silicon (c-Si) PV panel recovery process through several LCA/emergy-based indicators and their variation;

ii) quantify the energy, material and environmental costs of large scale WEEE recovery compared to the expected advantages;

iii) provide information and support to policy makers and stakeholders involved in WEEE decision making.

As previously shown in the case of power from slaughterhouse residues, the tool allows the user to enter all the relevant input flows for the assessment (Figure 23), in order to generate a set of performance indicators and graphs. The performance data obtained from the case study will be used to suggest improvements achievable at the sector (WEEE) and system (city) levels.



Sector Performance Calculator

#	Item	Unit		Variation	Sensitivity Adjusted Value
	Photovoltaic panel area (m^2)	0.884			
	Fabrication year	1986			
	Technology	Poly-Si			
	Dimensions (m)	1.3 x 0.68			
	Layers type (thickness)	glass-cell-PVF (43mm)			
1	**Machinery (furnace)**	item	1.00E+00	0%	1.00E+00
	Furnace price	€/item	1.50E+04	0%	1.50E+04
2	**Ammonia liquid**	kg	5.33E-05	0%	5.33E-05
	Ammonia price	€/kg	0.72	0%	7.20E-01
3	**Cement**	kg	4.53E-02	0%	4.53E-02
	Cement price	€/kg	0.06	0%	6.00E-02
4	**Chemical inorganic**	kg	8.14E-05	0%	8.14E-05
	Chemical inorganic price	€/kg	0.72	0%	7.20E-01
5	**Chemical organic**	kg	1.29E-05	0%	1.29E-05
	Chemical organic price	€/kg	0.72	0%	7.20E-01
6	**Chromium oxide, flakes**	kg	3.12E-08	0%	3.12E-08
	Chromium oxide price	€/kg	0.72	0%	7.20E-01
7	**Hydrochloric acid**	kg	4.88E-05	0%	4.88E-05
	Hydrochloric acid price	€/kg	0.72	0%	7.20E-01
8	**Iron (III) chloride**	kg	2.41E-05	0%	2.41E-05
	Iron (III) price	€/kg	0.72	0%	7.20E-01
9	**Quicklime**	kg	8.92E-03	0%	8.92E-03
	Quicklime price	€/kg	0.04	0%	4.00E-02
10	**Sodium hydroxide**	kg	5.07E-02	0%	5.07E-02
	Sodium hydroxide price	€/kg	0.72	0%	7.20E-01
11	**Titanium dioxide**	kg	1.53E-06	0%	1.53E-06
	Titanium dioxide price	€/kg	0.72	0%	7.20E-01
12	**Electricity**	kWh	1.91E+00	0%	1.91E+00
	Electricity cost	€/kWh	0.16	0%	1.60E-01
13	**Human labor**	hr	2.00E+00	0%	2.00E+00
Products					
	Glass scraps	g	8.14E+01	0%	8.14E+01
	Silicon scraps	g	9.79E+00	0%	9.79E+00
	Copper scraps	g	3.62E-01	0%	3.62E-01

Figure 23 – Sector level LCA/Emergy Inventory. Photovoltaic panel end-of-life case study (input flows are highlighted in blue and economic values of input flows are highlighted in red).

A systems diagram of the PV module production as well as the recovery process after use is shown in Figure 24, in order to show all the steps of the two processes, the existing links among components and the input and output flows, including a contribution from ecosystem and socio-economic parameters.

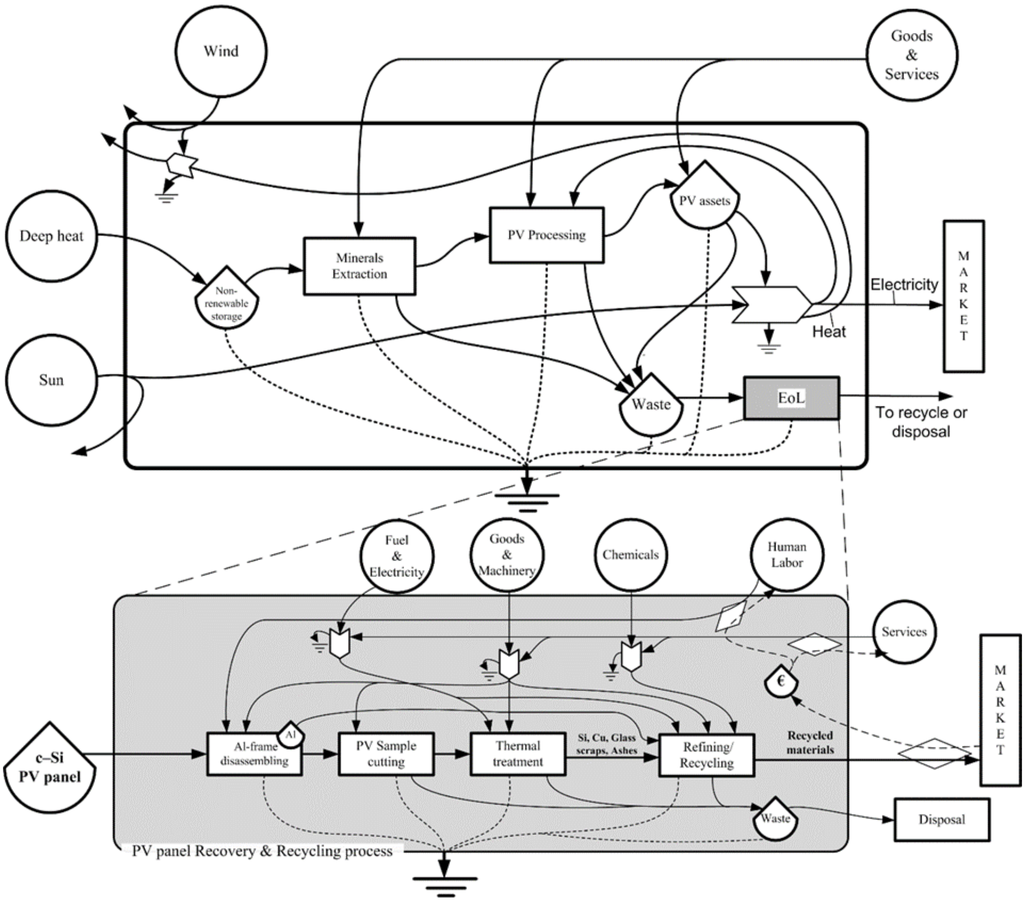


Figure 24 – System boundary of PV panel recovery process.

According to the prototype tool design, three different scenarios have been carried out:

- Improved Business as Usual (I-BAU) scenario: evaluating the system as it is, considering a statistical variation for relevant hotspot input flows, in order to explore sensitivity to data errors, uncertainty, unavailability.
- Technology-based Efficiency Improvement (TEI) scenario: considering a reduction of selected (more impacting items) energy and material input flows through technological improvement (better management, design, cohibentation, led).
- Eco-Efficiency Implementation (EEI) scenario: improving the environmental sustainability of the system level through substitution of energy and material hotspots with renewable or less environmental costly input flows.

The first scenario (Improved Business as Usual) has been developed considering a variation in the main impacting energy and material input flows considering a range of -10% and 10%. For PV panel end-of-life recovery case study the selected hotspots are electricity and sodium hydroxide. In the second scenario (Technology-based Efficiency Improvement) was suggested a better use of the main contributor to the environmental burdens. For this reason, the electricity input flow has been reduced in the range of -20% and 0%. The variation in the third scenario (Eco-Efficiency) has been related to the quality of the hotspot input flows. The electricity used to support the investigated sector system has been replaced partially by electricity coming from renewable sources (photovoltaic and wind), reducing the fossil fraction of the electricity mix of about 40%, with a variation range between -10% and 10%. The user can decide to insert a larger share of electricity coming from photovoltaic or wind sources, automatically lowering the fraction of electricity from the national mix.

Scenario n. 1 - Improved Business as Usual (I-BAU)

As highlighted by both LCA and EMA methods, the electricity input flow seems to be the more impacting item. Figure 25 shows the variation in the electricity input considering a variation of the first type (sensitivity oriented), in a range within -10% and +10%, applied to an input of electricity of 6.876E+06 J/m^2 panel. The resulting minimum is 6.19E+06 J/m^2 panel, while the maximum is 7.56E+06 J/m^2 panel. The mean value is 6.885E+06 J/m^2 panel.

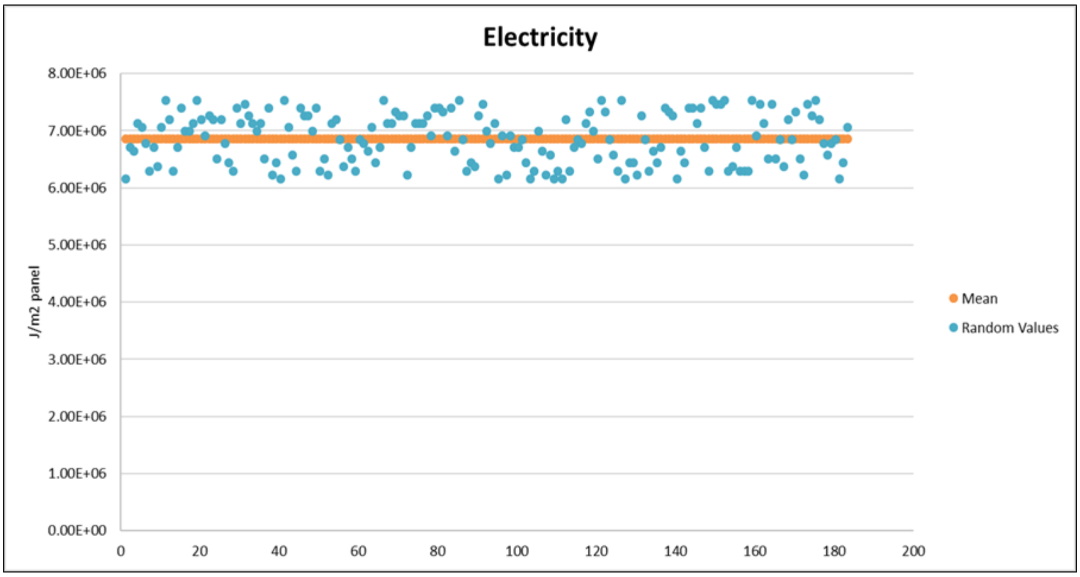


Figure 25 – Improved Business as Usual scenario: Electricity input flow variation within a range of -10% and +10%.

The same variation for sodium hydroxide input caused a mean value of 2.60E+01 g/m^2 panel, over a raw input of 2.62E+01 g/m^2 panel, with a minimum of 2.36E+01 g/m^2 panel, and a maximum of 2.88E+01 g/m^2 panel (Figure 26).

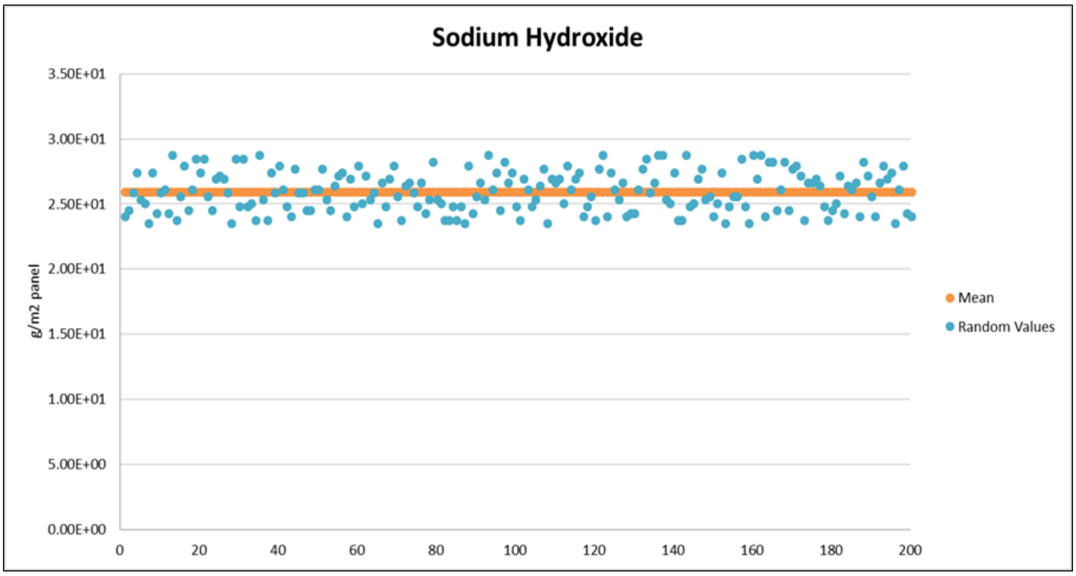


Figure 26 – *Improved Business as Usual scenario: Sodium Hydroxide input flow variation within a range of -10% and +10%.*

The assumed variations of the input flows will generate a variation in the resulting calculated indicators. As with the previous process level case, we will use selected indicators from the EMA approach to highlight the sustainability differences among scenarios. The total emergy U_{FU} (U associated to the Functional Unit, i.e. 1 m^2 of PV panel) quantifies the demand for environmental support in terms of use of locally renewable, locally non-renewable and imported emergy flows. The calculated UEVs express the same demand in relation to one unit of selected products (g of recovered materials, joule of PV electricity, etc). The same analytical procedure could be (and should be) done in the final version of the tool, for all the LCA, MuSIASEM and ASA indicators developed within the EUFORIE project.

Figure 27 shows the comparison between the calculated total emergy with and without L&S in order to show the importance of the inclusion of L&S in the evaluation. The added value in the use of EMA is the possibility to include in the analysis the direct flows of ecosystem services and the burden related to L&S (expressing the cost for infrastructure, know-how, information). Without taking into account the oscillating values of selected input flows, the U_{FU} with L&S shows a value of 3.82E+12 sej/m^2 panel, while U_{FU} without L&S is equal to 2.89E+12 sej/m^2 panel. These values are shown in Figure 27 together with their variations within the I-BAU scenario (variations applied to investigate the sensitivity or results). The minimum value of U with L&S is 3.54E+12 sej/m^2 panel, the maximum value is 4.11E+12 sej/m^2. The minimum value of U without L&S is 2.61E+12 sej/m^2 panel, the maximum is 3.18E+12 sej/m^2 panel.

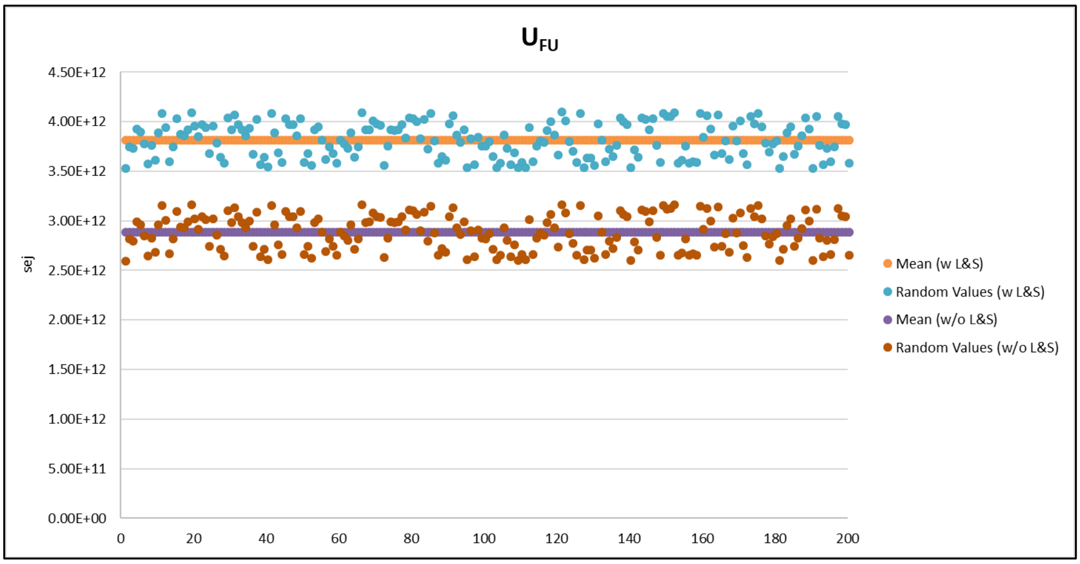


Figure 27 – Improved Business as Usual scenario: Sensitivity assessment of total emergy U_{FU} with and without L&S.

Moreover, the Unit Emergy Values (UEVs), for each recovered material (glass, silicon, copper) after PV panel thermal treatment, have been computed in order to understand the process efficiency, intending 'efficiency' as the ability to use less resources (less emergy) to produce a unit of product.

The UEV of recovered glass scraps without variation is 2.52E+08 sej/g with L&S and 1.90E+08 sej/g without L&S. UEV shows a minimum of 2.35E+08 sej/g and a maximum of 2.73E+08 sej/g with a mean value of 2.54E+08 sej/g with L&S; without L&S, the minimum is 1.73E+08 sej/g, the maximum is 2.11E+08 sej/g and the mean value is 1.92E+08 sej/g (Figure 28).

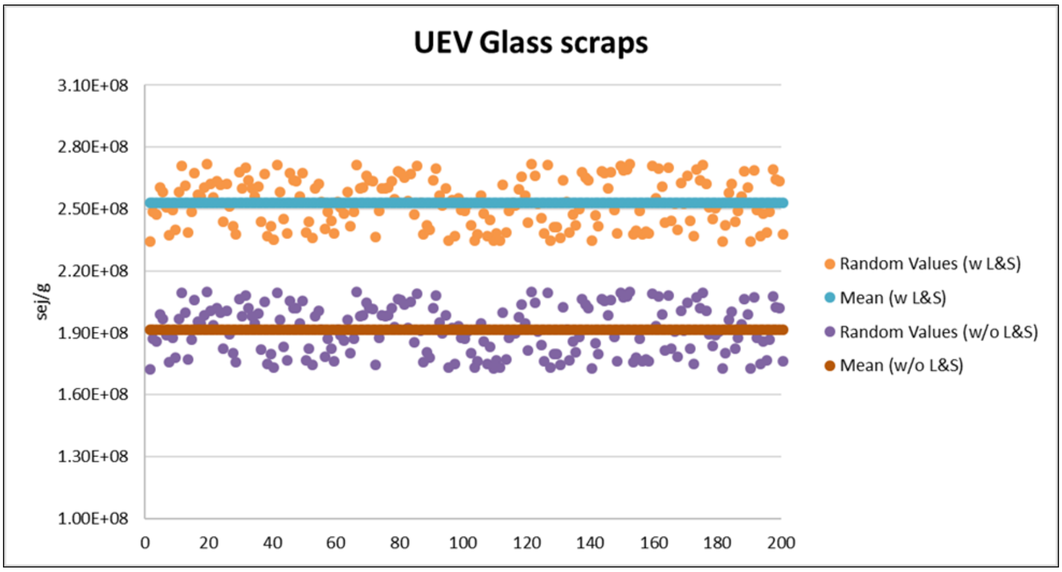


Figure 28 – *Improved Business as Usual scenario: Sensitivity assessment of UEV of glass scraps with and without L&S.*

The UEV of recovered silicon scraps without variation is 1.14E+09 sej/g with L&S and 8.66E+08 sej/g without L&S. UEV show a minimum of 1.05E+09 sej/g and a maximum of 1.22E+09 sej/g with a mean value of 1.13E+09 sej/g with L&S; without L&S, the minimum is 7.74E+08 sej/g, the maximum is 9.42E+08 sej/g and the mean value is 8.58E+08 sej/g (Figure 29).

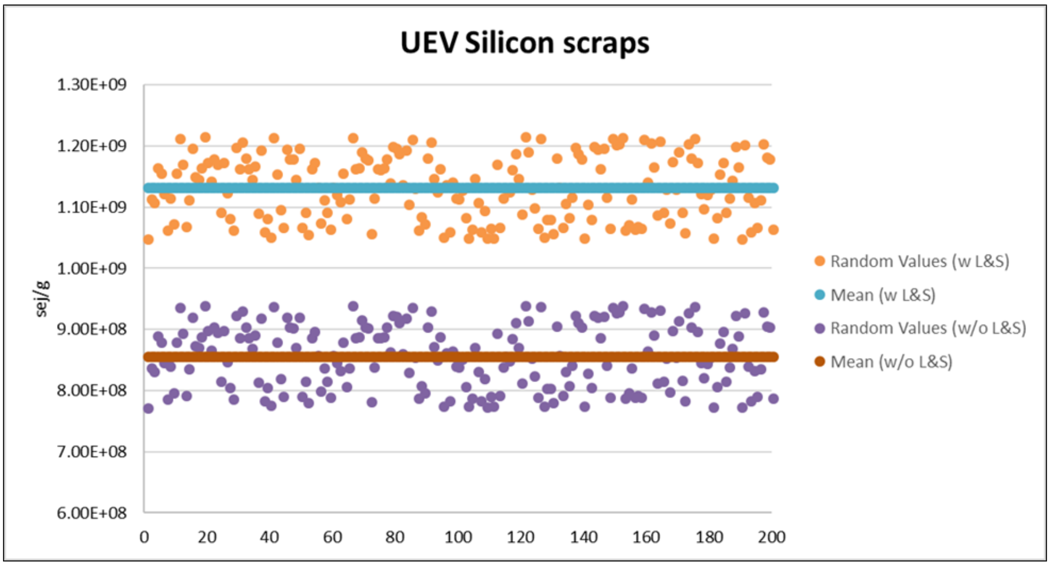


Figure 29 – Improved Business as Usual scenario: Sensitivity assessment of UEV of silicon scraps with and without L&S.

The UEV of recovered copper scraps without variation is 1.79E+10 sej/g with L&S and 1.35E+10 sej/g without L&S. UEV show a minimum of 1.66E+10 sej/g and a maximum of 1.93E+10 sej/g with a mean value of 1.80E+10 sej/g with L&S; without L&S, the minimum is 1.23E+10 sej/g, the maximum is 1.49E+10 sej/g and the mean value is 1.36E+10 sej/g (Figure 30).

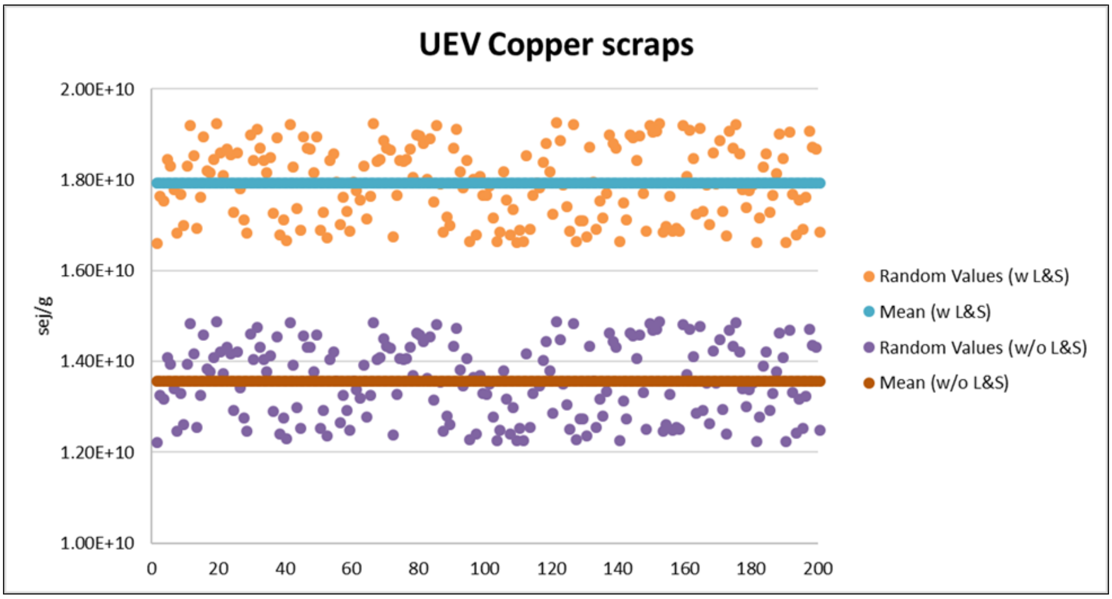


Figure 30 – Improved Business as Usual scenario: Sensitivity assessment of UEV of copper scraps with and without L&S.

Scenario n. 2 - Technology-based Efficiency Improvement (TEI)

In the second scenario (Technology-based Efficiency Improvement) a better use of the main inflow contributing to the environmental burdens (electricity) is suggested, as a potential result of an efficiency improvement of the process. For this reason, the electricity input flow has been reduced in the range of -20% and 0%. Such improvement can be easily achieved by replacing the used chemical oven by means of a more modern and better designed tool (e.g.: Snol, 2018; Bortek, 2018; Spectrum, 2018). Moreover, the date in this study have been obtained for a laboratory oven, not an industrial furnace, which generally would have a much higher efficiency (less electricity per unit of melted material). Figure 31 shows the lowered electricity input flow in the Technology-based Efficiency Improvement scenario. In this case, the mean observed value is 6.17E+06 J/m^2 panel, with a 20% reduction compared to the Business as Usual scenario (see Figure 25).

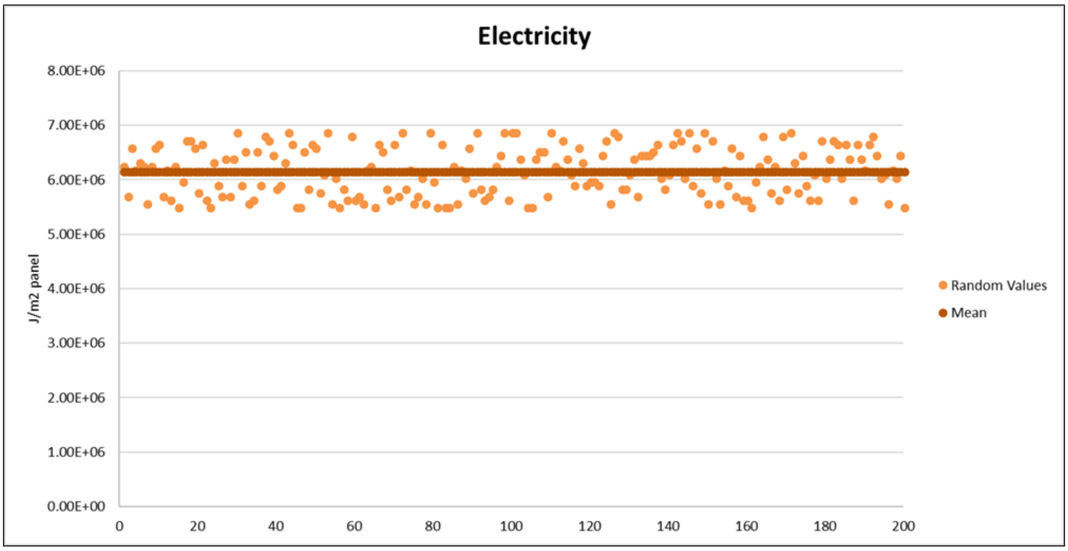


Figure 31 – Technology-based Efficiency Improvement scenario: Improvement of hotspot flow.

Figure 32 shows the total emergy U_{FU} for the second scenario, with a mean value of 3.53E+12 sej/m^2 panel with L&S and 2.60E+12 sej/m^2 panel without L&S.

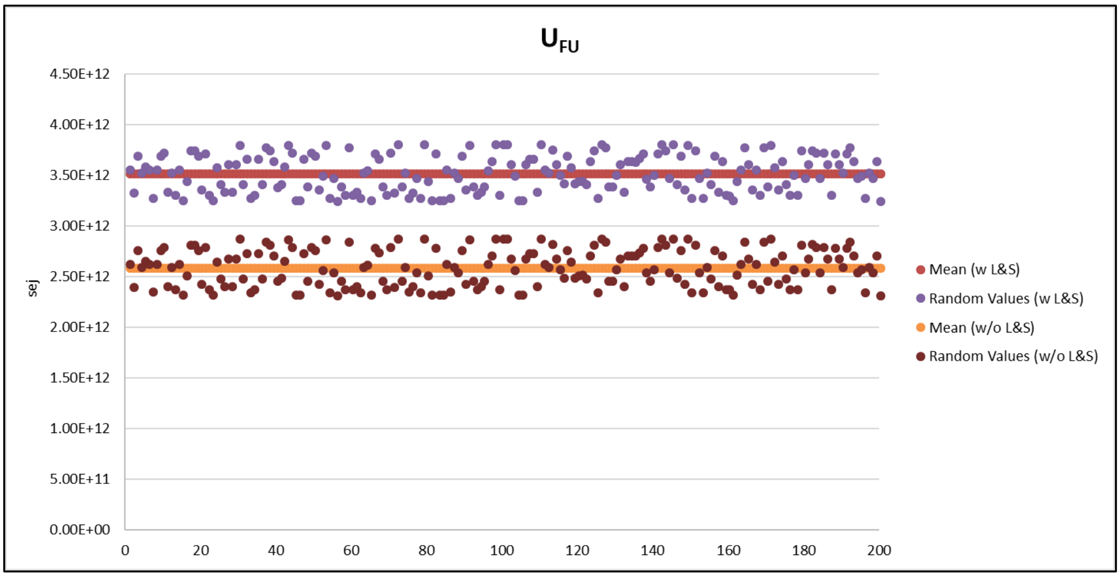


Figure 32 – Technology-based Efficiency Improvement scenario: Total Emergy U with and without L&S

Figure 33 reports the UEV values for recovered glass scraps with L&S (with a mean value of 2.34E+08 sej/g) and without L&S (with a mean value of 1.73E+08 sej/g).

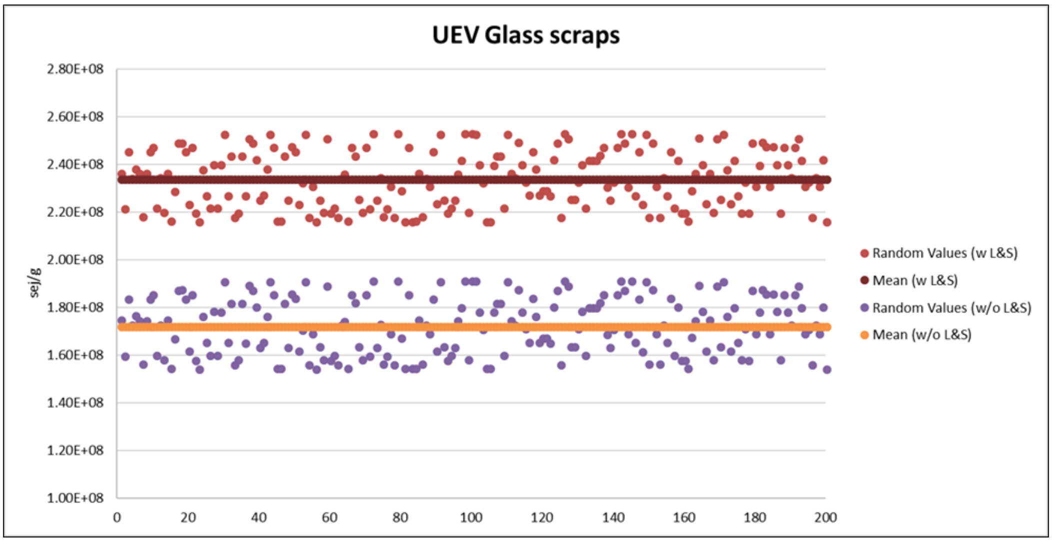


Figure 33 – Technology-based Efficiency Improvement scenario: UEV of glass scraps with and without L&S.

The UEV for recovered silicon scraps is equal to 1.05E+09 sej/g as a mean value with L&S, while it is 7.71E+08 sej/g as a mean value without L&S (Figure 34).

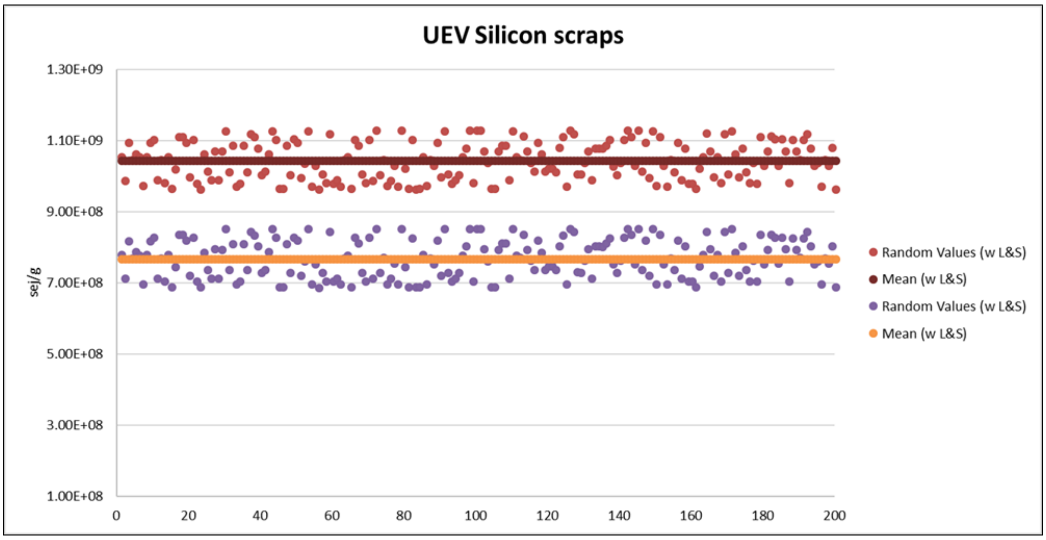


Figure 34 – Technology-based Efficiency Improvement scenario: UEV of silicon scraps with and without L&S.

Figure 35 reports the UEV values for recovered copper scraps with L&S (with a mean value of 1.66E+10 sej/g) and without L&S (with a mean value of 1.22E+10 sej/g).

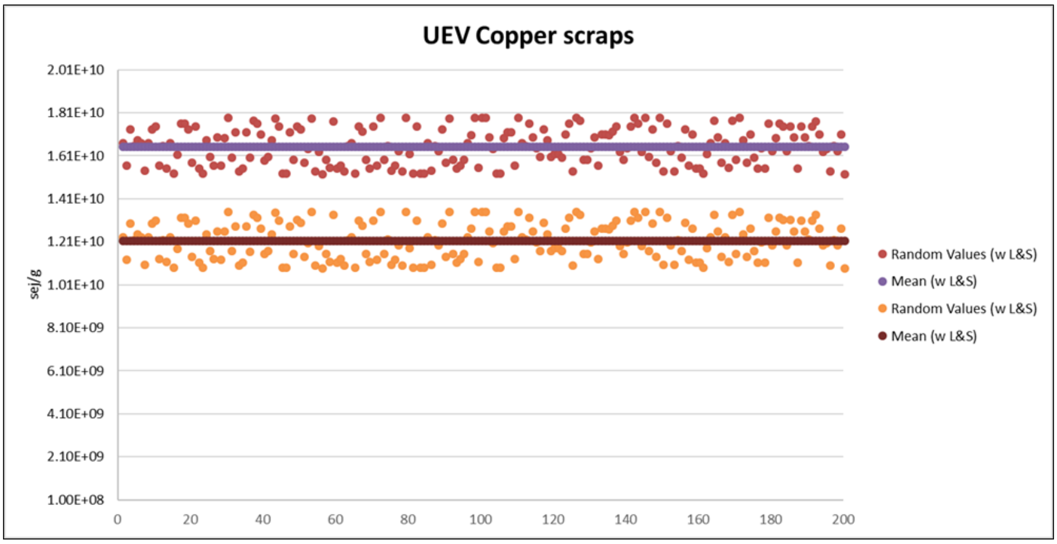


Figure 35 – Technology-based Efficiency Improvement scenario: UEV of copper scraps with and without L&S.

In general, all indicators show an environmental improvement deriving from the difference in the raw input of electric energy. The rationale is that similar or different oscillations can be simulated for all the input flows in order to calculate a final result for all the emergy indicators of interest, depending on the achievable efficiency improvement at the present state of technology.

Scenario n. 3. Eco-Efficiency Implementation (EEI)

Moving to the third scenario (Eco Efficiency Implementation), the raw input flow of the new electric energy mix (with partial substitution by renewable electricity) is shown in Figure 36, with a mean value of 4.10E+06 J/m^2 panel.

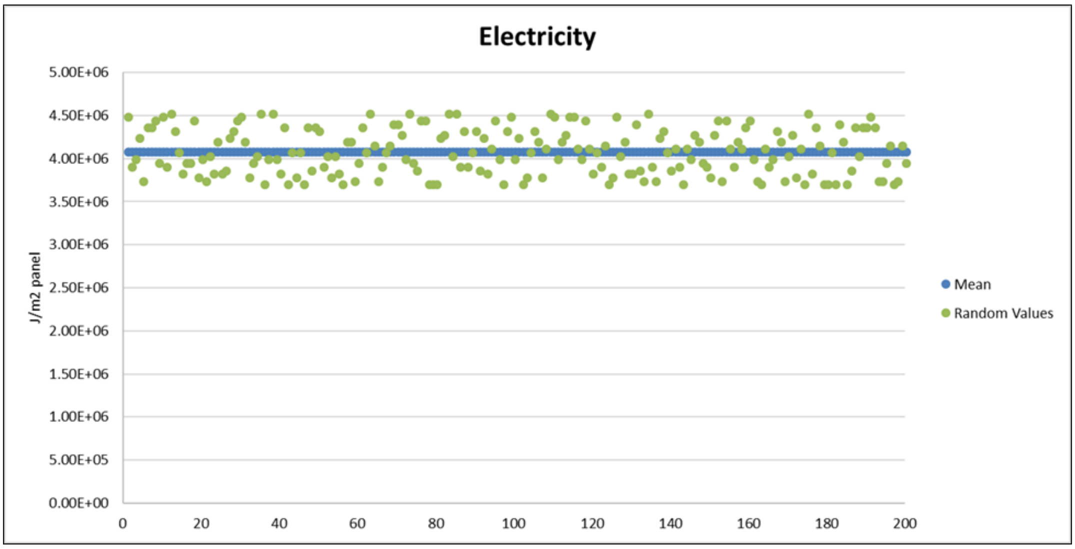


Figure 36 – Eco-Efficiency scenario: Improvement of hotspot flow.

The related total emergy U shows values of 2.72E+12 sej/m^2 panel and 1.79E+12 sej/m^2 panel respectively with and without L&S (Figure 37).

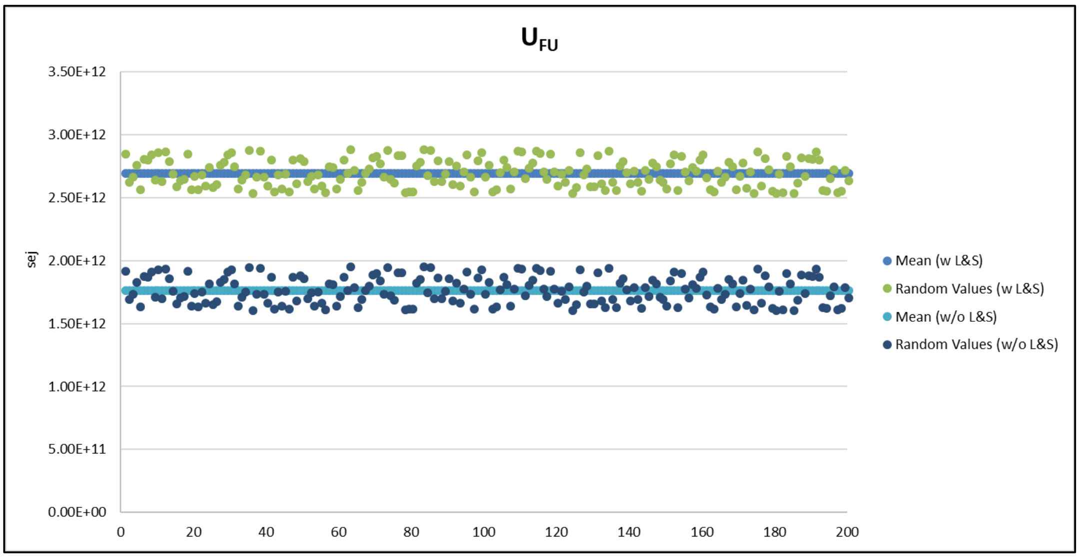


Figure 37 – Eco-Efficiency scenario: Total Emergy U with and without L&S.

Figure 38 reports the UEV values for recovered glass scraps with L&S (with a mean value of 1.80E+08 sej/g) and without L&S (with a mean value of 1.18E+08 sej/g).

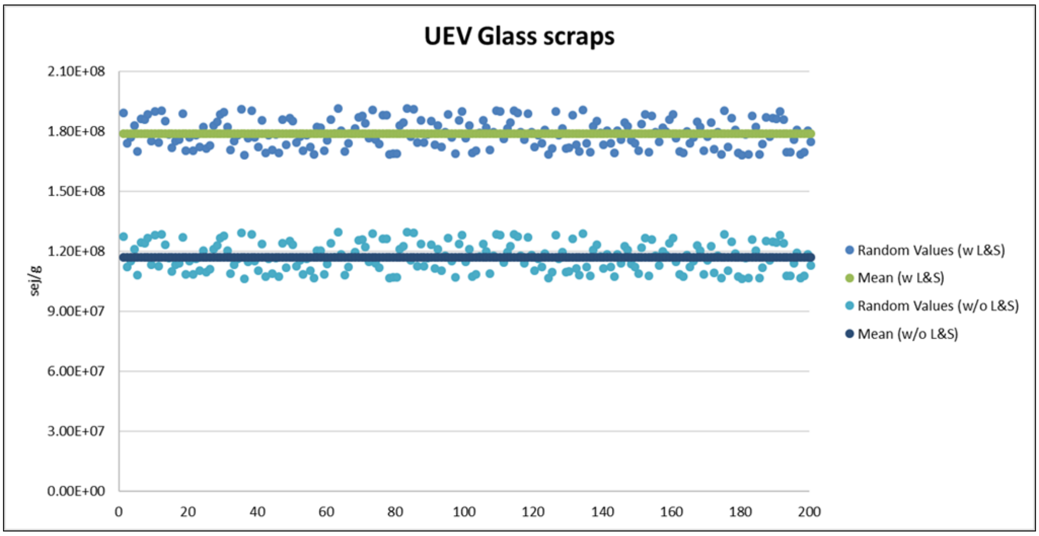


Figure 38 – *Eco-Efficiency scenario: UEV of glass scraps with and without L&S.*

The UEV for recovered silicon scraps is equal to 8.02E+08 sej/g as a mean value with L&S, while it is 5.26 E+08 sej/g as a mean value without L&S (Figure 39).

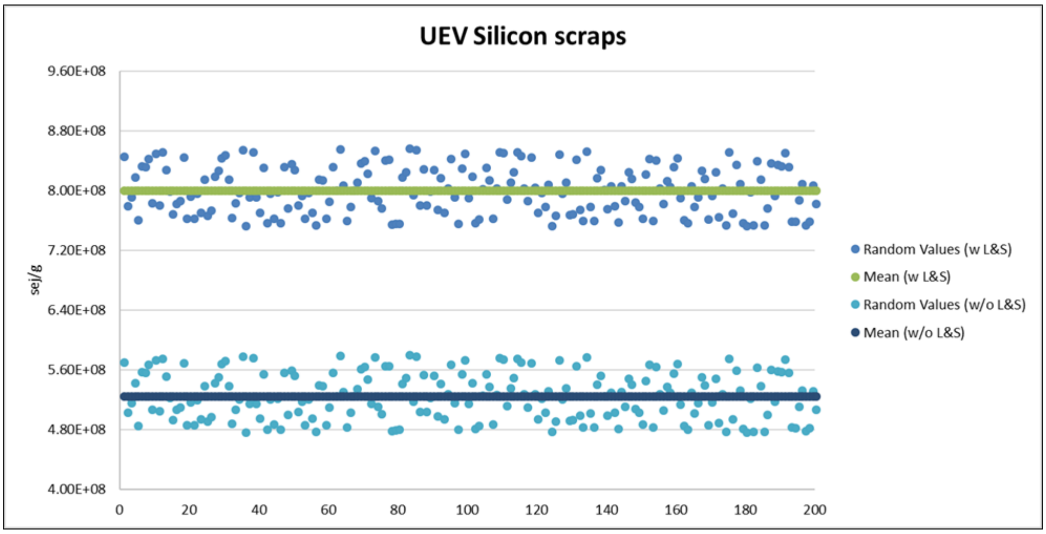


Figure 39 – Eco-Efficiency scenario: UEV of silicon scraps with and without L&S.

Figure 40 reports the UEV values for recovered copper scraps with L&S (with a mean value of 1.27E+10 sej/g) and without L&S (with a mean value of 8.34E+09 sej/g).

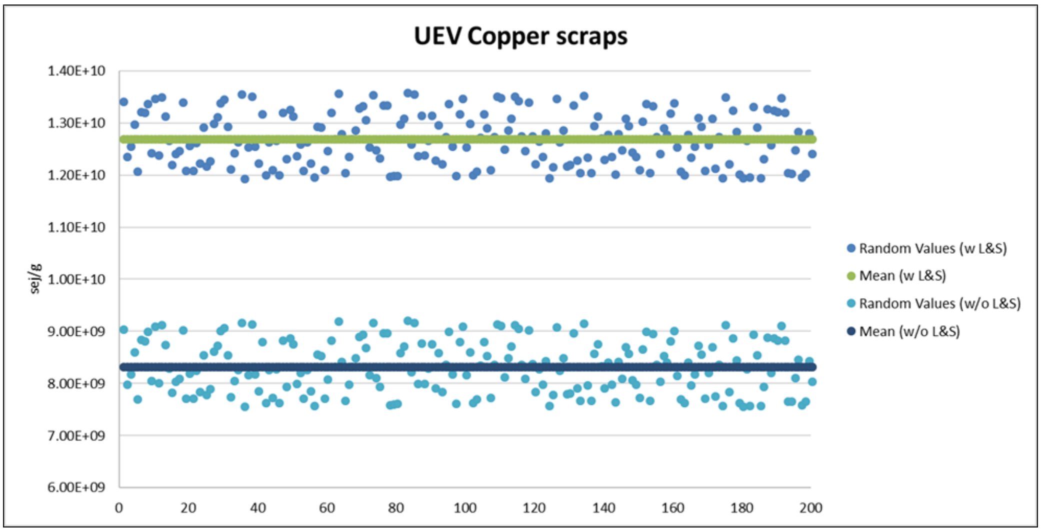


Figure 40 – Eco-Efficiency scenario: UEV of copper scraps with and without L&S.

The electricity-focused TEI scenario translates into U_{FU} mean values of 3.53E+12 sej/m^2 panel with L&S and 2.60E+12 sej/m^2 panel without L&S (Figure 32), respectively -7.6% and -10.0% compared to the I-BAU scenario. In addition, the electricity-focused EEI scenario translates into U_{FU} mean values of 2.72E+12 sej/m^2 panel with L&S and 1.79E+12 sej/m^2 panel (Figure 37), respectively -22.9% and -31.2% compared to TEI scenario. As regards to glass scraps, UEV_{glass} calculated under the TEI scenario displays values of 2.34E+08 sej/g with L&S and 1.73E+08 sej/J without L&S (Figure 33), about 9% lower than the I-BAU scenario; UEV_{glass} calculated under the EEI scenario shows values of 1.80E+08 sej/g with L&S and 1.18E+08 sej/g without L&S (Figure 19) about 27% lower than the TEI scenario. As to silicon scraps, $UEV_{silicon}$ calculated under the TEI scenario displays values of 1.05E+09 sej/g with L&S and 7.71E+08 sej/g without L&S (Figure 34), about 8% lower than the I-BAU scenario; $UEV_{silicon}$ calculated under the EEI scenario shows values of 8.02E+08 sej/g with L&S and 5.23E+08 sej/g without L&S (Figure 39) about 28% lower than the TEI scenario. With reference to copper scraps, UEV_{copper} calculated under the TEI scenario displays values of 1.66E+10 sej/g with L&S and 1.22E+10 sej/g without L&S (Figure 35), about 9% lower than the I-BAU scenario; UEV_{copper} calculated under the EEI scenario shows values of 1.27E+10 sej/g with L&S and 8.34E+09 sej/g without L&S (Figure 40) about 27% lower than the TEI scenario.

3.4. Energy and material efficiency benefits from PV panels and other WEEE recovery within a circular economy perspective.

Despite the considerable emergy demand in handling PV waste, the electricity production from PV can be proven to be still more environmentally sustainable than the fossil one. Brown et al. (2012) compared the overall efficiency of electricity production by CdTe PV modules over 30 years with power based on fossil oil, proving PV power to be much more environmentally sound than fossil powered plants, in spite of claims of low energy efficiency of panels and large land occupation. However, these authors did not include the EoL costs, which left the cost-benefit assessment still uncertain. The results of this study show that even adding the recovery costs of decommissioned panels to the cost of production and operation of PV panels, the final emergy demand is still much lower than for a conventional fossil powered plant. In fact, as shown in Figure 41, the emergy invested for the electricity production from PV - also including the recovery of PV panels - results to be always lower than for an equivalent electricity generation from a conventional energy source.

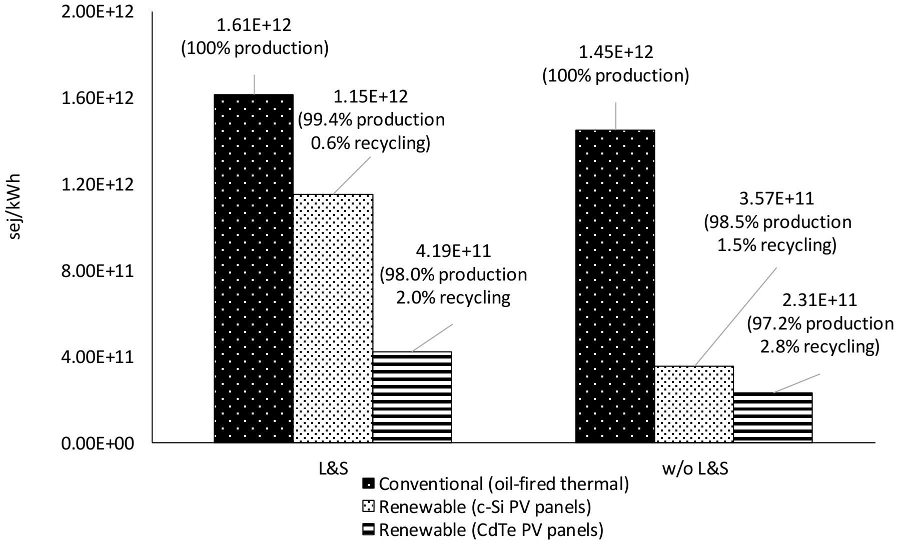


Figure 41 – Comparison between the emergy cost of PV and fossil powered electricity generation, over a 30 years' life time, with and without the emergy for Labor and Services (in the case of fossil electricity generation, results don't include additional costs for decommissioning and recycling).

An appropriate end-of-life management of PV panels is a prerequisite for the sustainability of the entire PV electricity supply chain, which calls for increased efforts to assess and monitor impacts and benefits. The scenario analysis addressed by means of integration of LCA/Emergy methods, provided recommendations and suggestions to improve the environmental feasibility of the investigated sector level. Through the three investigated scenarios, the reduction of the main hotspot (electricity) due to the Technology-based Efficiency Improvement scenario results to be less sustainable than the complete substitution of the main contributor to the total burdens (Eco-Efficiency Implementation scenario). Indeed, the analysis of the Italian electricity mix, has pointed out that its larger component comes from fossil fuels (about 70%). This result underlines that 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. Furthermore, the analysis showed that the recovery process of the PV panels has clear advantages from the energy and environmental points of view. The main environmental benefits arise from the recovery of aluminium and silicon. Nevertheless, the other recovered materials (glass, copper) also provide non-negligible benefits. It is to be noted that the main impact of the PV panel production is generated by the silicon wafer and its high embodied energy. Therefore, given the expected increase of the volume of the PV panels waste in the future, the WEEE sector is going to become a dominating recovery activity at the urban level, so that a well-designed recovery process has to be carried out; this has to include all high value materials such as silicon (feedstock, wafer or cell) and silver. Recycling would be facilitated by appropriate PV module design, for easier separation of components.

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Chapter 4 - System level. Urban energy metabolism, the case study of the City of Napoli

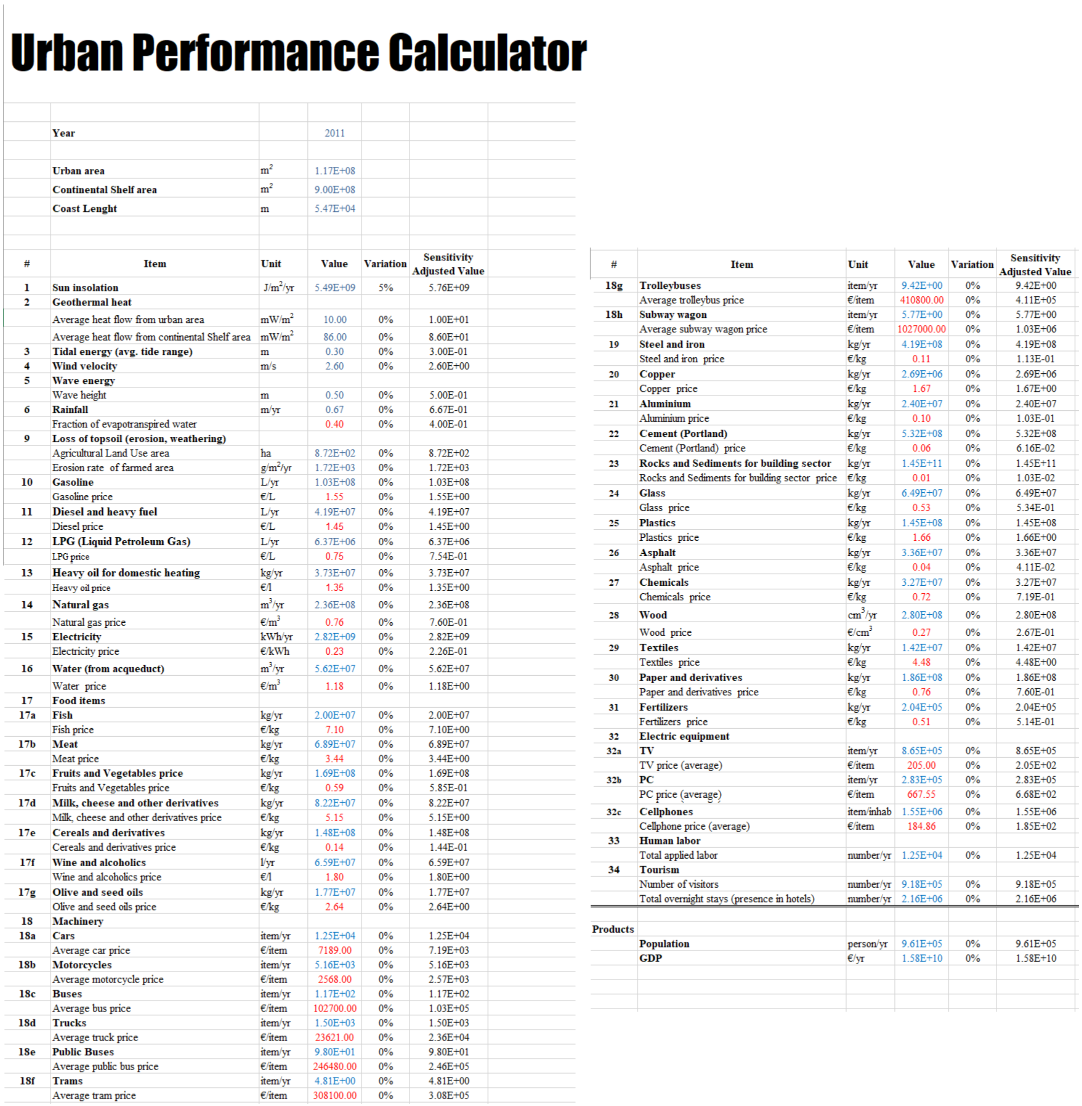
Cities are the engine of economic development and human wellbeing, but their dynamics needs to be supported by the convergence of large flows of material and energy resources. Assessing a city resource metabolism becomes increasingly crucial, not only concerning the relation with the environment as a source or a sink, but also concerning the internal dynamics of resource exchange among city components and sectors. The selected urban system is the City of Naples, located in Campania region, southern Italy (detailed description of the investigated system reported in Viglia et al., 2017, work carried out in the framework of EUFORIE project).

4.1 The Urban system. Description and operation (LCA)

In order to evaluate the environmental performance at **system level**, the spreadsheet prototype tool "Urban Performance Calculator" (Figure 42) has been applied to an urban system, by merging LCA and Emergy method as already shown with the process and sector levels. As already pointed out, this tool allows to: i) evaluate the urban environmental sustainability; ii) measure the urban system metabolism through several LCA/emergy-based indicators and their variation; iii) provide information and support to policy makers and other stakeholders involved in decision making.

The user interface in Figure 2 allows to enter all the relevant input flows for the assessment, in order to deliver a set of performance indicators and graphs.

In this early stage, the tool accounts for all input data (inventory analysis), standardized LCA/Emergy calculation procedures and the final emergy and LCA indicators computation, within the framework of the LCA/Emergy assessment of the city of Naples (Italy). According to the standard LCA procedures the system level has been investigated considering all input and output flows related to Naples Urban Metabolism (Figure 43). The functional unit chosen for the LCA of Naples urban metabolism is 1 m^2, whilst the selected system boundary is shown in Figure 43 including all inputs and outputs within the municipality of Naples.



Urban Performance Calculator

Year		2011	
Urban area	m^2	1.17E+08	
Continental Shelf area	m^2	9.00E+08	
Coast Lenght	m	5.47E+04	

#	Item	Unit	Value	Variation	Sensitivity Adjusted Value
1	**Sun insolation**	J/m^2/yr	5.49E+09	5%	5.76E+09
2	**Geothermal heat**				
	Average heat flow from urban area	mW/m^2	10.00	0%	1.00E+01
	Average heat flow from continental Shelf area	mW/m^2	86.00	0%	8.60E+01
3	**Tidal energy (avg. tide range)**	m	0.30	0%	3.00E-01
4	**Wind velocity**	m/s	2.60	0%	2.60E+00
5	**Wave energy**				
	Wave height	m	0.50	0%	5.00E-01
6	**Rainfall**	m/yr	0.67	0%	6.67E-01
	Fraction of evapotranspired water		0.40	0%	4.00E-01
9	**Loss of topsoil (erosion, weathering)**				
	Agricultural Land Use area	ha	8.72E+02	0%	8.72E+02
	Erosion rate of farmed area	g/m^2/yr	1.72E+03	0%	1.72E+03
10	**Gasoline**	L/yr	1.03E+08	0%	1.03E+08
	Gasoline price	€/L	1.55	0%	1.55E+00
11	**Diesel and heavy fuel**	L/yr	4.19E+07	0%	4.19E+07
	Diesel price	€/L	1.45	0%	1.45E+00
12	**LPG (Liquid Petroleum Gas)**	L/yr	6.37E+06	0%	6.37E+06
	LPG price	€/L	0.75	0%	7.54E-01
13	**Heavy oil for domestic heating**	kg/yr	3.73E+07	0%	3.73E+07
	Heavy oil price	€/l	1.35	0%	1.35E+00
14	**Natural gas**	m^3/yr	2.36E+08	0%	2.36E+08
	Natural gas price	€/m^3	0.76	0%	7.60E-01
15	**Electricity**	kWh/yr	2.82E+09	0%	2.82E+09
	Electricity price	€/kWh	0.23	0%	2.26E-01
16	**Water (from acqueduct)**	m^3/yr	5.62E+07	0%	5.62E+07
	Water price	€/m^3	1.18	0%	1.18E+00
17	**Food items**				
17a	**Fish**	kg/yr	2.00E+07	0%	2.00E+07
	Fish price	€/kg	7.10	0%	7.10E+00
17b	**Meat**	kg/yr	6.89E+07	0%	6.89E+07
	Meat price	€/kg	3.44	0%	3.44E+00
17c	**Fruits and Vegetables price**	kg/yr	1.69E+08	0%	1.69E+08
	Fruits and Vegetables price	€/kg	0.59	0%	5.85E-01
17d	**Milk, cheese and other derivatives**	kg/yr	8.22E+07	0%	8.22E+07
	Milk, cheese and other derivatives price	€/kg	5.15	0%	5.15E+00
17e	**Cereals and derivatives**	kg/yr	1.48E+08	0%	1.48E+08
	Cereals and derivatives price	€/kg	0.14	0%	1.44E-01
17f	**Wine and alcoholics**	l/yr	6.59E+07	0%	6.59E+07
	Wine and alcoholics price	€/l	1.80	0%	1.80E+00
17g	**Olive and seed oils**	kg/yr	1.77E+07	0%	1.77E+07
	Olive and seed oils price	€/kg	2.64	0%	2.64E+00
18	**Machinery**				
18a	**Cars**	item/yr	1.25E+04	0%	1.25E+04
	Average car price	€/item	7189.00	0%	7.19E+03
18b	**Motorcycles**	item/yr	5.16E+03	0%	5.16E+03
	Average motorcycle price	€/item	2568.00	0%	2.57E+03
18c	**Buses**	item/yr	1.17E+02	0%	1.17E+02
	Average bus price	€/item	102700.00	0%	1.03E+05
18d	**Trucks**	item/yr	1.50E+03	0%	1.50E+03
	Average truck price	€/item	23621.00	0%	2.36E+04
18e	**Public Buses**	item/yr	9.80E+01	0%	9.80E+01
	Average public bus price	€/item	246480.00	0%	2.46E+05
18f	**Trams**	item/yr	4.81E+00	0%	4.81E+00
	Average tram price	€/item	308100.00	0%	3.08E+05
18g	**Trolleybuses**	item/yr	9.42E+00	0%	9.42E+00
	Average trolleybus price	€/item	410800.00	0%	4.11E+05
18h	**Subway wagon**	item/yr	5.77E+00	0%	5.77E+00
	Average subway wagon price	€/item	1027000.00	0%	1.03E+06
19	**Steel and iron**	kg/yr	4.19E+08	0%	4.19E+08
	Steel and iron price	€/kg	0.11	0%	1.13E-01
20	**Copper**	kg/yr	2.69E+06	0%	2.69E+06
	Copper price	€/kg	1.67	0%	1.67E+00
21	**Aluminium**	kg/yr	2.40E+07	0%	2.40E+07
	Aluminium price	€/kg	0.10	0%	1.03E-01
22	**Cement (Portland)**	kg/yr	5.32E+08	0%	5.32E+08
	Cement (Portland) price	€/kg	0.06	0%	6.16E-02
23	**Rocks and Sediments for building sector**	kg/yr	1.45E+11	0%	1.45E+11
	Rocks and Sediments for building sector price	€/kg	0.01	0%	1.03E-02
24	**Glass**	kg/yr	6.49E+07	0%	6.49E+07
	Glass price	€/kg	0.53	0%	5.34E-01
25	**Plastics**	kg/yr	1.45E+08	0%	1.45E+08
	Plastics price	€/kg	1.66	0%	1.66E+00
26	**Asphalt**	kg/yr	3.36E+07	0%	3.36E+07
	Asphalt price	€/kg	0.04	0%	4.11E-02
27	**Chemicals**	kg/yr	3.27E+07	0%	3.27E+07
	Chemicals price	€/kg	0.72	0%	7.19E-01
28	**Wood**	cm^3/yr	2.80E+08	0%	2.80E+08
	Wood price	€/cm^3	0.27	0%	2.67E-01
29	**Textiles**	kg/yr	1.42E+07	0%	1.42E+07
	Textiles price	€/kg	4.48	0%	4.48E+00
30	**Paper and derivatives**	kg/yr	1.86E+08	0%	1.86E+08
	Paper and derivatives price	€/kg	0.76	0%	7.60E-01
31	**Fertilizers**	kg/yr	2.04E+05	0%	2.04E+05
	Fertilizers price	€/kg	0.51	0%	5.14E-01
32	**Electric equipment**				
32a	**TV**	item/yr	8.65E+05	0%	8.65E+05
	TV price (average)	€/item	205.00	0%	2.05E+02
32b	**PC**	item/yr	2.83E+05	0%	2.83E+05
	PC price (average)	€/item	667.55	0%	6.68E+02
32c	**Cellphones**	item/inhab	1.55E+06	0%	1.55E+06
	Cellphone price (average)	€/item	184.86	0%	1.85E+02
33	**Human labor**				
	Total applied labor	number/yr	1.25E+04	0%	1.25E+04
34	**Tourism**				
	Number of visitors	number/yr	9.18E+05	0%	9.18E+05
	Total overnight stays (presence in hotels)	number/yr	2.16E+06	0%	2.16E+06
Products					
	Population	person/yr	9.61E+05	0%	9.61E+05
	GDP	€/yr	1.58E+10	0%	1.58E+10

Figure 42 – System level LCA/Emergy Inventory. The City of Naples case study (input flows are highlighted in blue and economic values of input flows are highlighted in red).

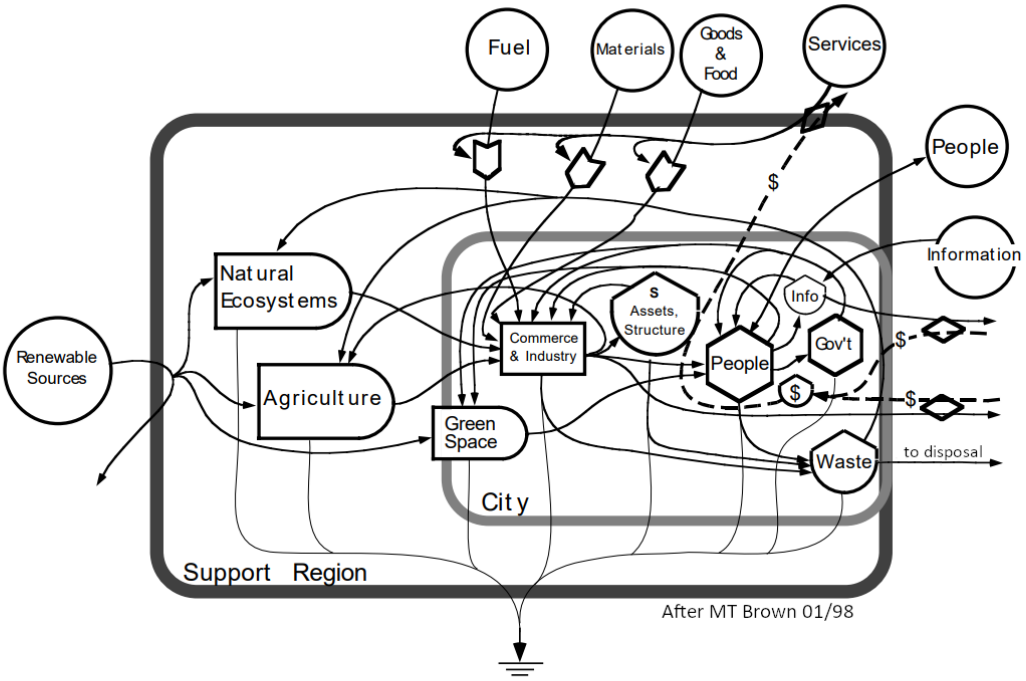


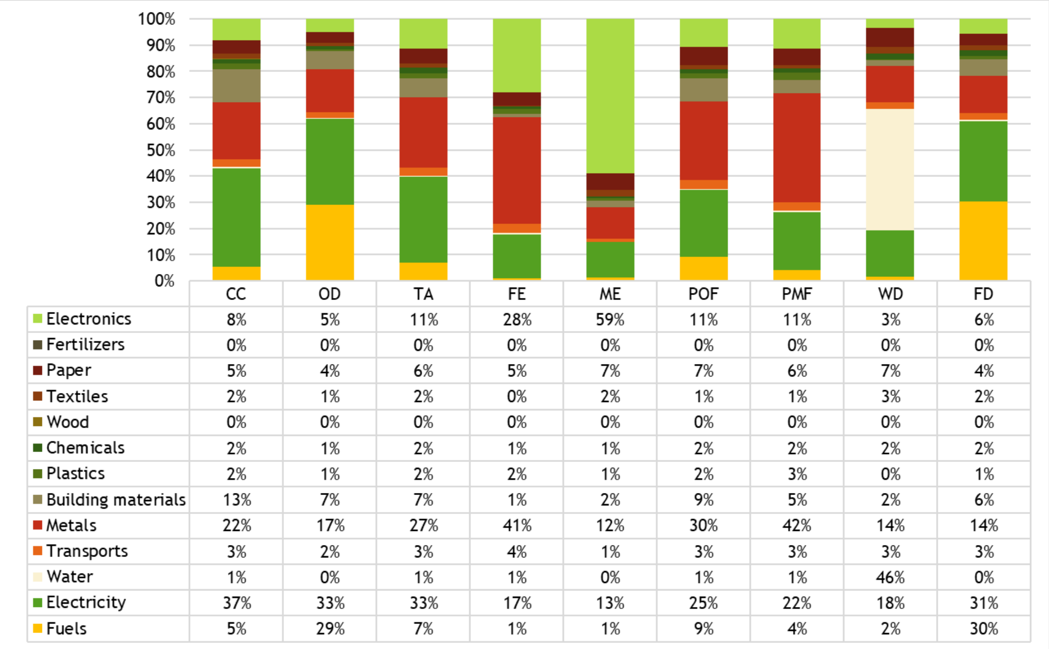
Figure 43 – System boundary of urban system.

Table 5 shows the LCA impact categories explored in this study. The LCA impact assessment has been performed by means of LCA software SimaPro 8.2.0 and the ReCiPe Midpoint hierarchist (H) impact assessment method v. 1.12. In order to ascertain the environmental load of Naples urban system, the impact assessment has been based on characterization diagrams showing the breakdown into different impact sources. In this way the main hotspots for each investigated impact category and for the whole urban metabolism has been assessed.

Table 5 – LCA impact categories.

Impact category	Abbreviation	Unit
Climate change	CC	kg CO_2 eq
Ozone depletion	OD	kg CFC-11 eq
Terrestrial acidification	TA	kg SO_2 eq
Freshwater eutrophication	FE	kg P eq
Marine eutrophication	ME	kg N eq
Photochemical oxidant formation	POF	kg NMVOC eq
Particulate matter formation	PMF	kg PM_{10} eq
Water depletion	WD	m^3
Fossil depletion	FD	kg oil eq

In Figure 44, the different contributions of each input flow are shown. As clearly appears, the main contributors are electricity (sharing about 25% of impacts as average value among all investigated impact categories), followed by metals (24%), electronics (16%) and fuels (10%) input flows.



	CC	OD	TA	FE	ME	POF	PMF	WD	FD
■ Electronics	8%	5%	11%	28%	59%	11%	11%	3%	6%
■ Fertilizers	0%	0%	0%	0%	0%	0%	0%	0%	0%
■ Paper	5%	4%	6%	5%	7%	7%	6%	7%	4%
■ Textiles	2%	1%	2%	0%	2%	1%	1%	3%	2%
■ Wood	0%	0%	0%	0%	0%	0%	0%	0%	0%
■ Chemicals	2%	1%	2%	1%	1%	2%	2%	2%	2%
■ Plastics	2%	1%	2%	2%	1%	2%	3%	0%	1%
■ Building materials	13%	7%	7%	1%	2%	9%	5%	2%	6%
■ Metals	22%	17%	27%	41%	12%	30%	42%	14%	14%
■ Transports	3%	2%	3%	4%	1%	3%	3%	3%	3%
■ Water	1%	0%	1%	1%	0%	1%	1%	46%	0%
■ Electricity	37%	33%	33%	17%	13%	25%	22%	18%	31%
■ Fuels	5%	29%	7%	1%	1%	9%	4%	2%	30%

Figure 44 – Characterization graph shows the relative contribution of the main input flows to the total burdens of the urban system of Naples.

4.2 Assessment scenarios at urban system level

From the LCA results, it appears evident that cities are very demanding in terms of environmental services, so that an evaluation only based on climate change or the combustion-generated emissions would be very limited. In order to better understand the dynamics and the performance of the urban system, the LCA evaluation has been integrated with the EMA method (EUFORIE early prototype tool), to take into account the interrelations between the free natural resources and the socio-economic parameters. For this reason, the system level was analyzed exploring the usual three different scenarios:

- Improved Business as Usual (I-BAU) scenario: evaluating the system as it is, considering a statistical variation for relevant hotspot input flows, in order to explore sensitivity to data errors, uncertainty, unavailability.
- Technology-based Efficiency Improvement (TEI) scenario: considering a reduction of selected (more impacting items) energy and material input flows through technological improvement (better management, design, cohibentation, led). In this specific case, assuming the replacement of a fraction of the lighting system by means of Light Emission Diodes (LED), which generally allow a lower consumption around -70%
- Eco-Efficiency Implementation (EEI) scenario: improving the environmental sustainability of the system level through substitution of energy and material hotspots with renewable or less environmental costly input flows.

The first scenario (I-BAU) was developed considering a variation in the main impacting energy and material input flows considering a range of -10% and 10%. For the Naples case study the selected hotspots are electricity, natural gas and steel & iron. In the second scenario (Technology-based Efficiency Improvement) a better use of the main contributors to the environmental burdens was suggested. For this reason the electricity input flow has been reduced in the range of -20% and 0%

assuming replacement of a fraction of the lighting system by means of Light Emission Diodes (LED), which generally allow a lower consumption around 70%. The variation in the third scenario (Eco-Efficiency Implementation, EEI) has been related to the quality of the hotspot input flows. The electricity supporting the investigated urban system has been partially replaced by electricity coming from lower emergy intensity (UEV) sources (photovoltaic and wind), reducing the fossil fraction of the electricity mix of about 40%. The user can decide to replace a larger share of electricity coming from photovoltaic or wind sources, automatically lowering the fraction of electricity from the national mix.

Scenario N.1 - Improved Business as Usual (I-BAU)

Figure 45 shows the variation in the electricity input considering a variation of the first type, in a range within -10% and +10%, applied to an input of electricity of 1.03E+16 J/yr. As already pointed out, such oscillations express options of sensitivity analysis, namely help understand the effect on the final product characteristics of quantitative errors or temporary variations due to contingent factors. If only one factor oscillates, the final result will show a variation proportional to both the oscillation factor and the weight of the oscillating inflow within the "basket" of input resources. The resulting minimum in our case is 9.12E+15 J/yr, while the maximum is 1.11E+16 J/yr.

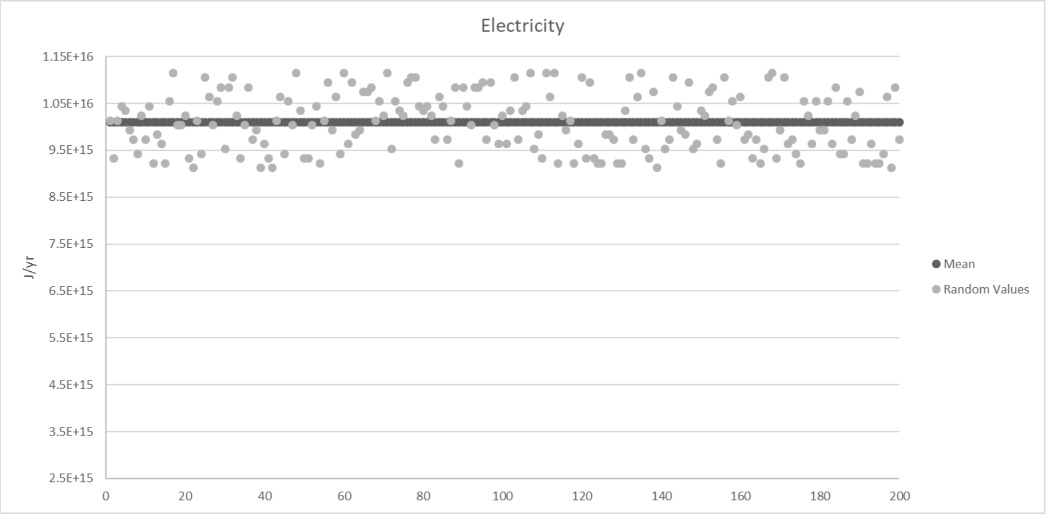


Figure 45 – Improved Business as Usual scenario: Electricity input flow variation within a range of -10% and +10%.

With the same -10%/+10% variation, natural gas input flow oscillates between a low 8.37E+15 J/yr and a higher 1.02E+16 J/yr (Figure 46).

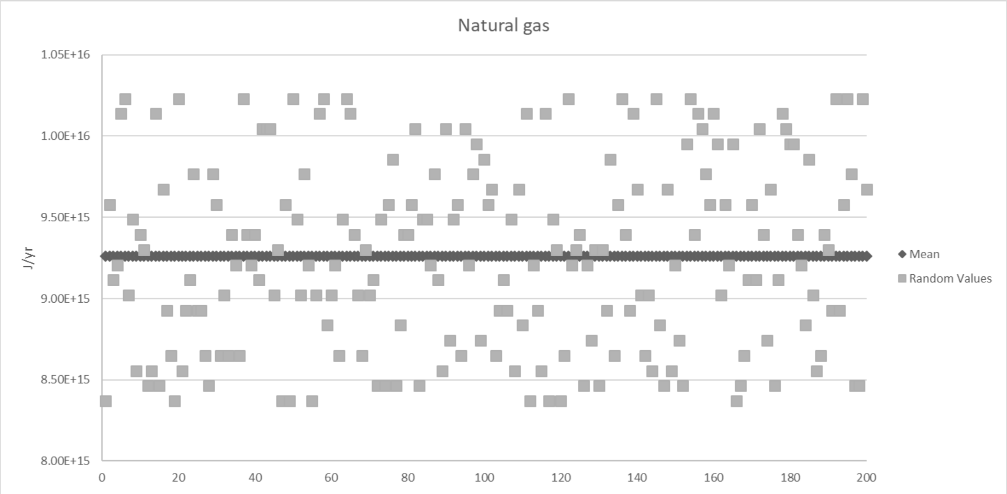


Figure 46 – Improved Business as Usual scenario: Natural gas input flow variation within a range of -10% and +10%.

In a like manner, the steel and iron input flow ranges from a minimum of 3.77E+11 g/yr to a maximum of 4.61E+11 g/yr (Figure 47).

Figure 47 – *Improved Business as Usual scenario: Steel & Iron input flow variation within a range of -10% and +10%.*

The joint variation in these input flows generates a variation in the resulting calculated emergy indicators, taken as reference indicators to show how the tool works. The emergy indicators are shown below. The total emergy U shows the environmental loading in terms of use of renewable local input emergy flows, imported non-renewable emergy flows, and non-renewable local emergy flows (Figure 48 and Figure 49). U has been calculated considering the accounting of Labor and Services (L&S) in Figure 48 and without L&S in Figure 49. Without taking into account the inflow oscillations, U with L&S shows a value of 1.91E+22 sej/yr, while U without L&S is equal to 8.73E+21 sej/yr. Figure 48 and Figure 49 show the variation of U respectively with and without L&S. The minimum value of U with L&S is 1.88E+22 sej/yr, the maximum value is 1.93E+22. The minimum value of U without L&S is 8.51E+21 sej/yr, the maximum is 8.94E+21 sej/yr.

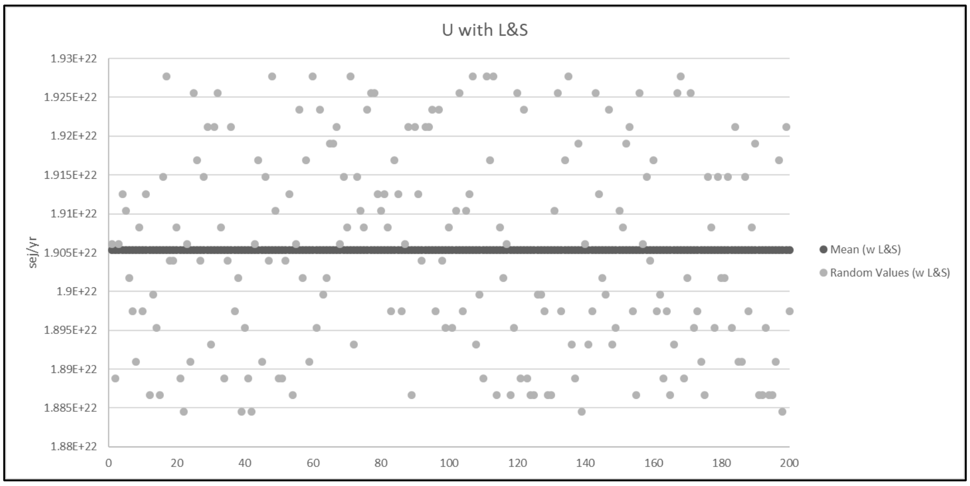


Figure 48 – *Improved* Business as Usual scenario: Variation of U with L&S

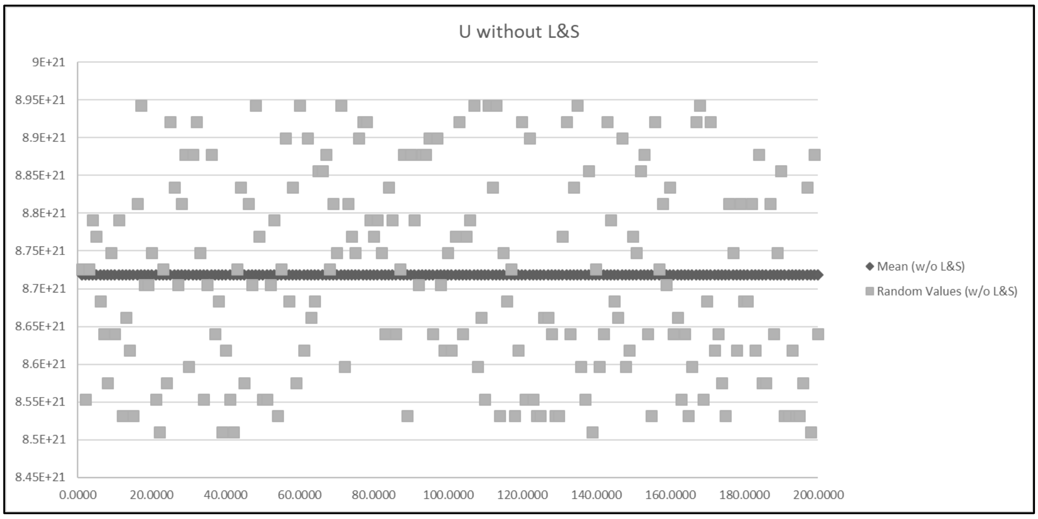


Figure 49 – Improved Business as Usual scenario: Variation of U without L&S

Figure 50 shows the comparison between the calculated total emergy with and without L&S in order to show the importance of the inclusion of L&S in the evaluation. The added value in the use of EMA is the possibility to include in the analysis the inflows of direct ecosystem services, the time needed for resource generation and the burden related to L&S (infrastructure, information, know-how).

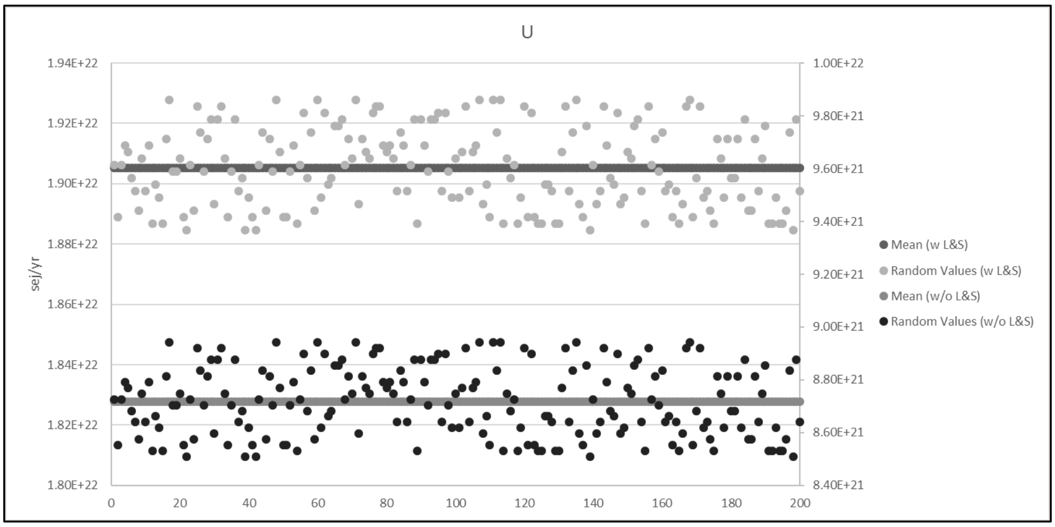


Figure 50 – Improved Business as Usual scenario: **–** Total emergy U with and without L&S

Other emergy-based indicators (and their oscillations) have been calculated in order to underline the ability of the system to exploit and make available local resources by investing outside inputs (Environmental Yield Ratio – EYR), the loading in terms of purchased resources (Environmental Loading Ratio – ELR), the percent of renewable resources used (%Ren) and the whole sustainability (Environmental Sustainability Index – ESI) by quantifying changes in openness and loading occurred in both technological processes and economies.

The Emergy Yield Ratio (EYR) without inflow oscillations is 1.04 (with L&S) and 1.02 (without L&S). EYR show a minimum of 1.0421 and a maximum of 1.0432 with L&S; without L&S the minimum is 1.0182, and the maximum is 1.0191 (Figure 51).

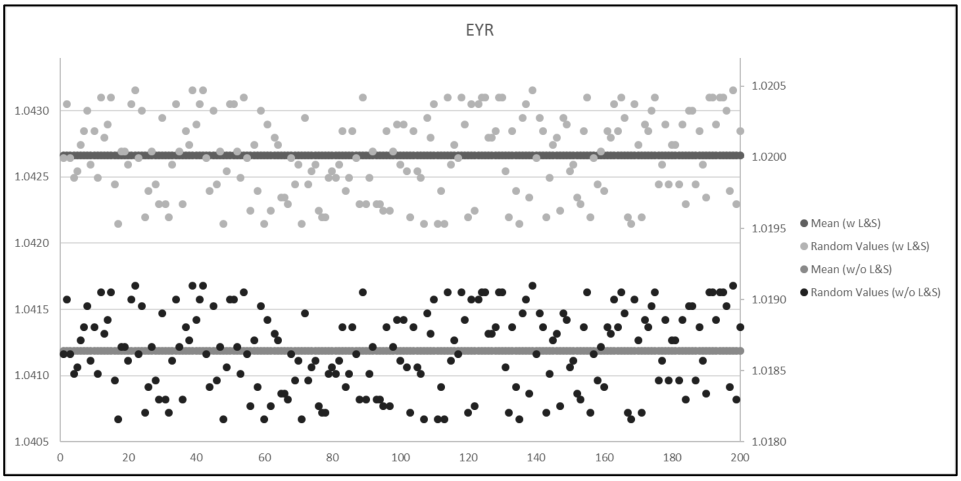


Figure 51 – Improved Business as Usual scenario: EYR with and without L&S

The Environmental Loading Ratio (ELR) without variation of inflows is equal to 23.46 with L&S and to 53.77 without L&S. Introducing the inflow oscillations, it shows a minimum of 23.18 and a maximum of 23.73, with L&S; instead, without L&S the minimum is 52.38 and the maximum is 55.09, (Figure 52).

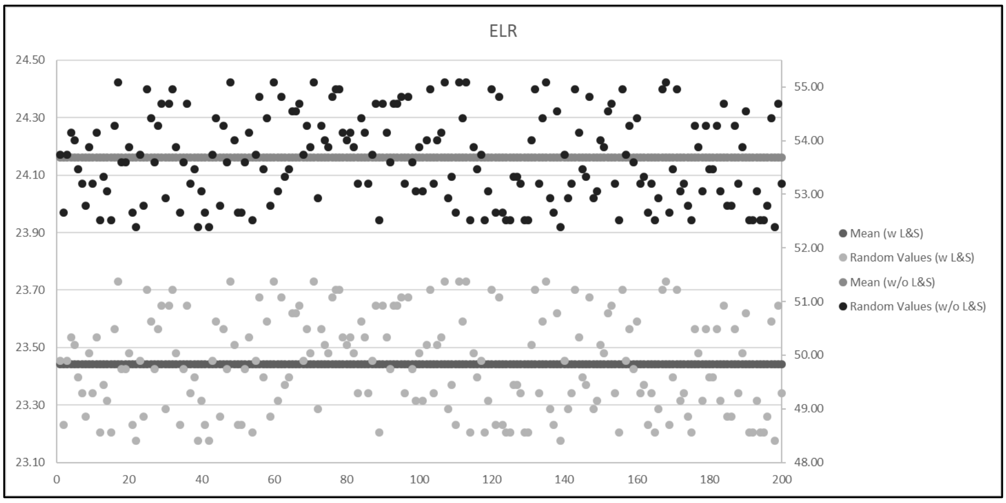


Figure 52 – Improved Business as Usual scenario: ELR with and without L&S

The renewable fraction (%Ren) of the emergy supporting the city of Naples is 4% with L&S and a low 2% without L&S. Introducing the oscillations, a minimum of 4.044% and a maximum of 4.136% with L&S is calculated. Instead, the minimum value is 1.783% and the maximum is 1.873% without L&S (Figure 53).

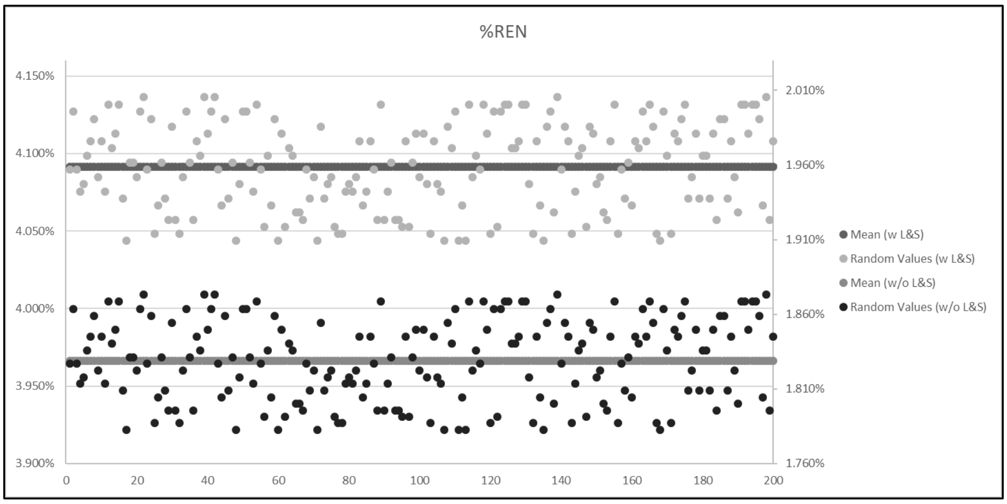


Figure 53 – Improved Business as Usual scenario: %Ren with and without L&S

In a like manner, the Emergy Sustainability Index (ESI) shows values of 0.04 (with L&S) and 0.02 (without L&S). Taking into account the oscillations of the main inflow, the ESI with L&S shows a minimum value of 0.0439 and a maximum of 0.450. Without including L&S, the minimum value is 0.0185 and the maximum 0.0195. Figure 54 plots data of both ESI with and without L&S.

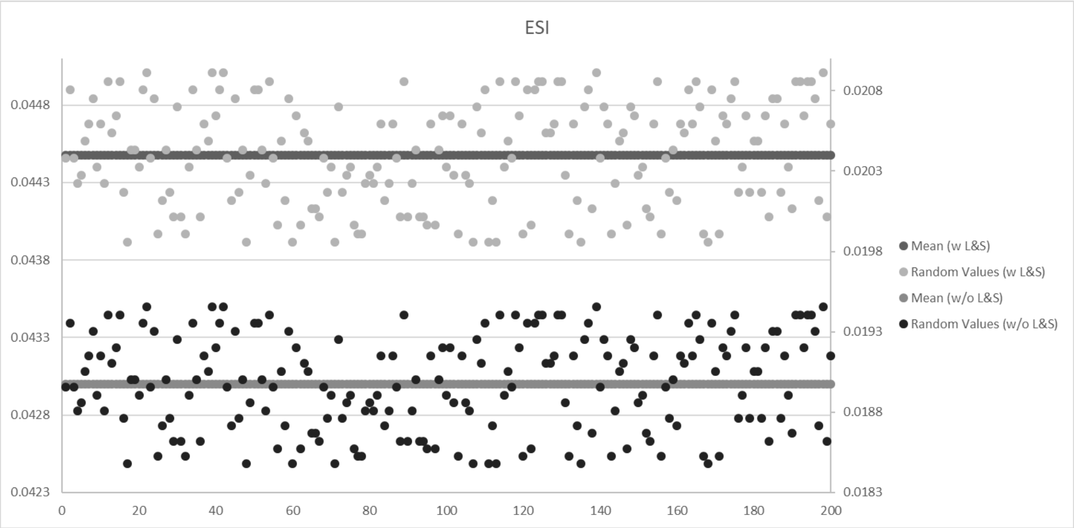


Figure 54 – Improved Business as Usual scenario: ESI with and without L&S

The LCA and emergy results show the crucial importance of energy expenditures within the city system. This is an important starting point for planners of urban sustainability, in that a small achievement or degradation locally may have unexpected positive or negative consequences globally. Both applied methods (LCA and EMA) provided a picture of the dependence of cities on fossil energy and material resources, ecosystems services and human labor. The methods measure 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 were identified (electricity and other fuels, minerals and metals) in the I-BAU scenario. Therefore, in order to increase the environmental sustainability of the whole investigated urban system and achieve improvements, also the TEI and EEI scenarios have been computed.

Scenario n.2 - The Technology-based Efficiency Improvement (TEI)

As highlighted by both LCA and EMA methods, the electricity input flow seems to be the more impacting item, therefore both scenarios (Technology-based Efficiency Improvement-TEI and Eco-Efficiency Implementation-EEI) were investigated by acting of the electricity inflow. A variation of electricity between -20% and 0% was assumed for the Technology-based Efficiency Improvement scenario. As mentioned earlier, the replacement of a fraction of the urban lighting system by means of Light Emission Diodes was assumed (LEDs generally allow a -70% lower consumption compared to the conventional bulbs).

Figure 55 shows the improvement of the electricity input flows relative to the Technology-based Efficiency Improvement scenario. In this case the mean observed value is 9.17E+15 J/yr, with a 10% reduction compared to the Business as Usual scenario (previous Figure 45).

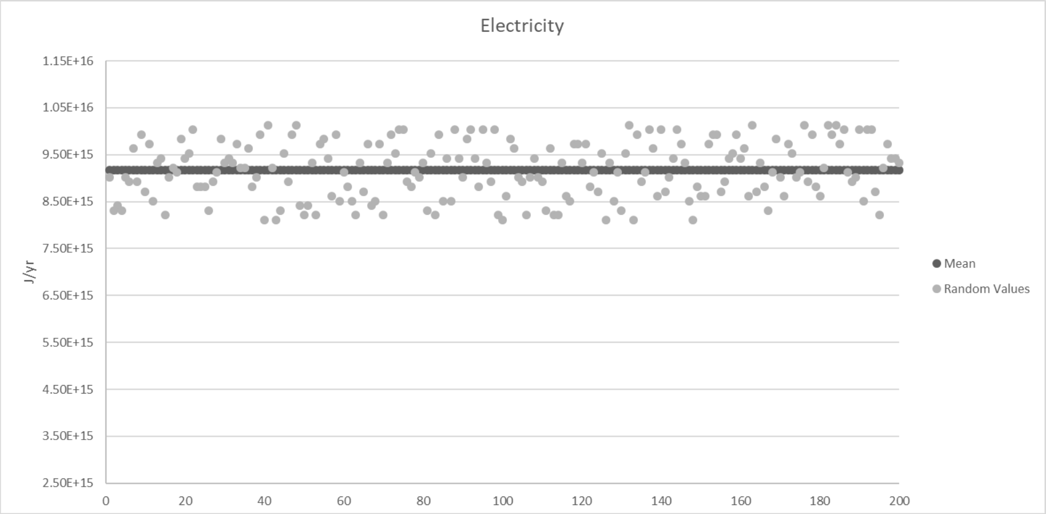


Figure 55 – Technology-based Efficiency Improvement scenario: Improvement of hotspot flow.

As with previous cases dealing with process and sector levels, the assumed technological improvement (more efficient lighting via LEDs or better lighting design) would lead to a much lower total emergy demand and improved performance indicators. Figure 56 shows the total emergy U for the TEI scenario, with a mean value of 1.87E+22 with L&S (about 2.5% lower than I-BAU) and 8.34E+21 without L&S (about 5% lower than I-BAU). In general, all emergy-based performance indicators of the urban system show an improvement deriving from the decreased raw input of electric energy, although percentages of change are not very large, due to the fact that the emergy contribution of electricity to total emergy U is only respectively 12% and 20% with and without L&S and therefore improving electricity means affecting only a fraction of the total emergy demand.

In a like manner EYR, ELR, %REN and ESI were calculated (with and without L&S) and results are diagrammed as follows:

- Figure 57, EYR values with L&S (with a mean value of 1.04) and without L&S (with a mean value of 1.02);
- Figure 58, ELR values with L&S (with a mean value of 22.96) and without L&S (with a mean value of 51.33);
- Figure 59, %REN values with L&S (4.17% – mean value) and without L&S (1.9% – mean value);
- Figure 60: ESI values with and without L&S (respectively 0.045 and 0.020).

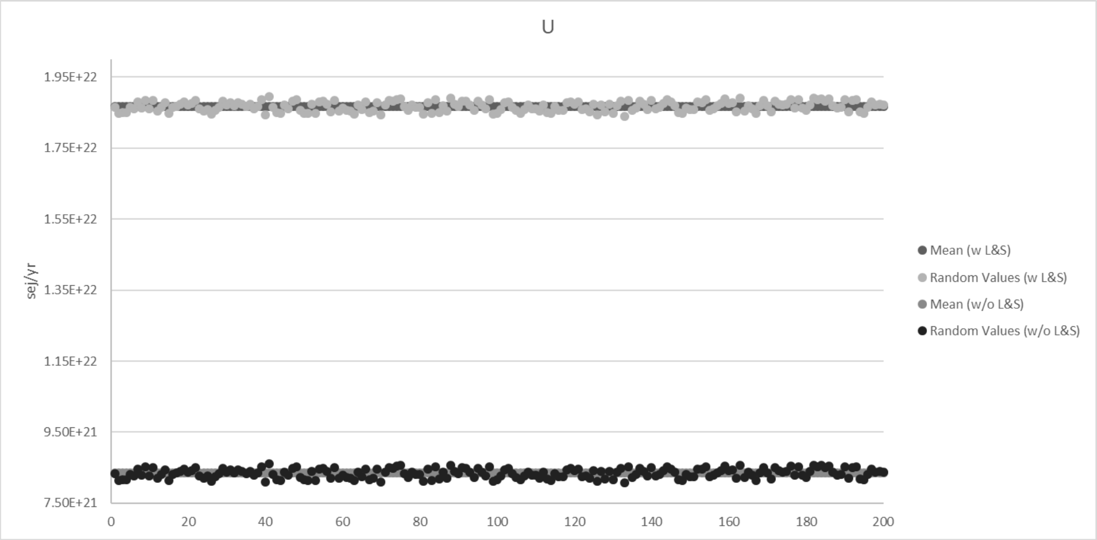


Figure 56 – Technology-based Efficiency Improvement: Total Emergy U with and without L&S

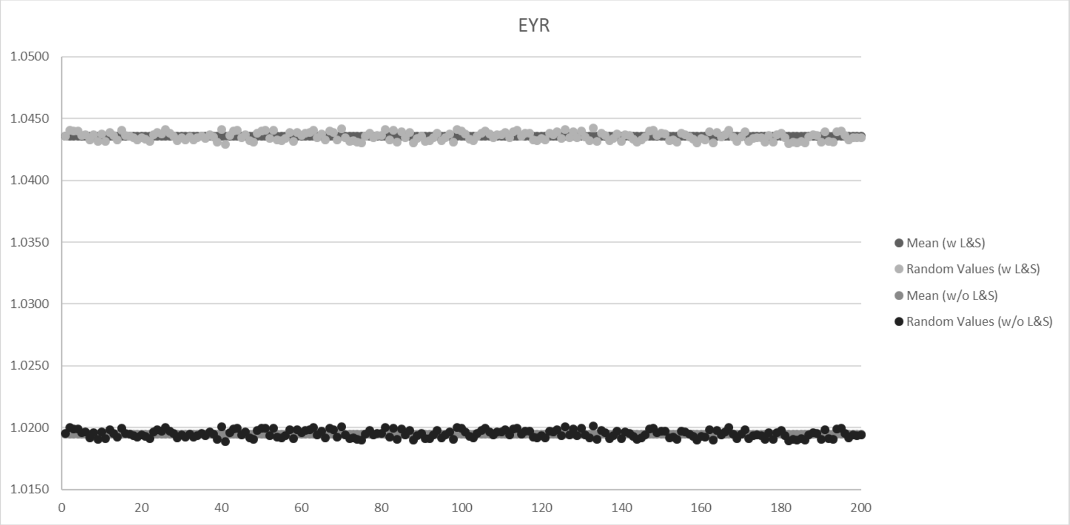


Figure 57 – Technology-based Efficiency Improvement scenario: EYR with and without L&S.

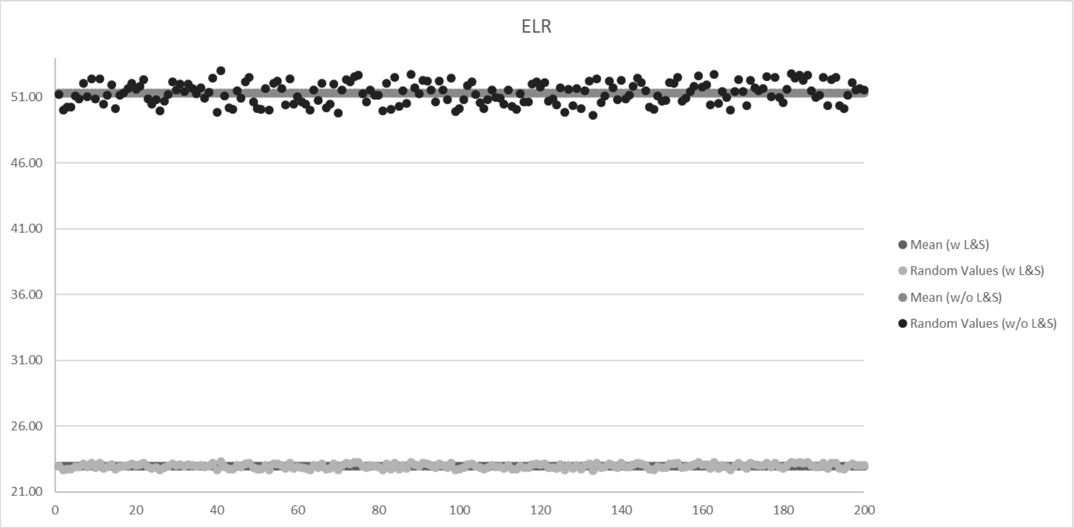


Figure 58 – Technology-based Efficiency Improvement scenario: ELR with and without L&S.

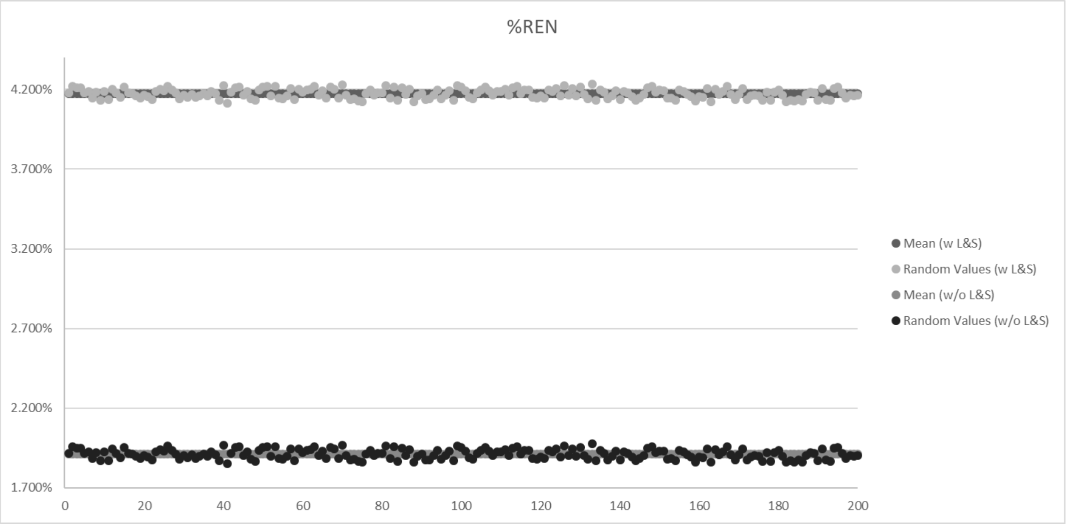


Figure 59 – Technology-based Efficiency Improvement scenario: %Ren with and without L&S.

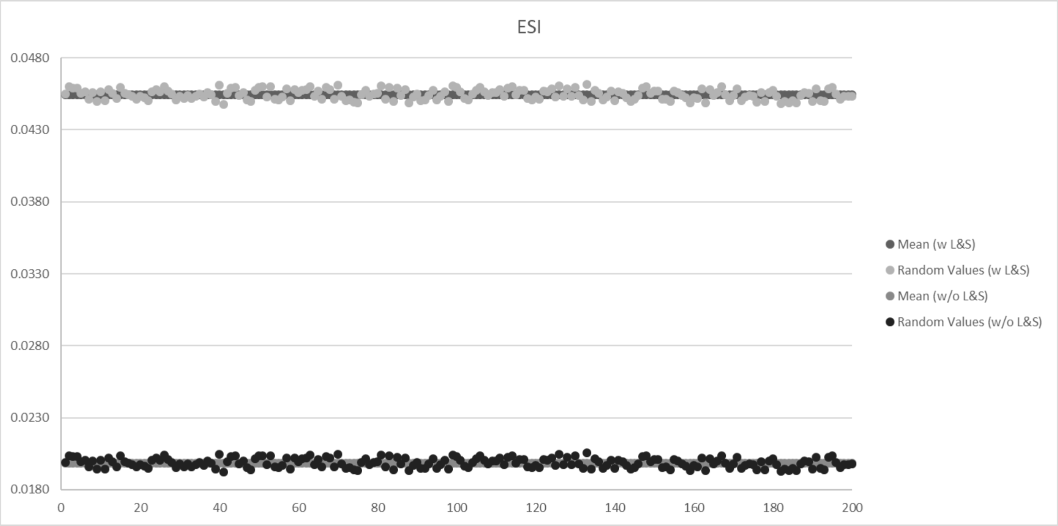


Figure 60 – Technology-based Efficiency Improvement scenario: ESI with and without L&S.

Scenario N. 3 - The Eco-Efficiency Implementation (EEI)

Moving to the Eco-Efficiency Implementation scenario, the substitution of 40% of the standard mix of electricity by means of electricity from renewable sources (i.e. characterized by a lowed UEV; Brown et al., 2012) was assumed. Due to such replacement, also the emergy of L&S associated to the electricity flow was adjusted proportionally to the nonrenewable/renewable fractions, according to Brown et al. (2012). However, considering that the services associated to electricity account for only 10% of its total emergy in the case of fossil source and to 45% in the case of PV source (Brown et al., 2012) and that the electricity total inflow at urban level only accounts for about 20% of total urban use without L&S and about 12% with L&S (Viglia et al., 2017), the variation due to the lower services associated to the 40% replacement is negligible, in the order of 1%.

The replacement of 40% of fossil-based electricity by means of photovoltaic electricity (characterized by a much lower Unit Emergy Value UEV) translates into a lower (direct and embodied) energy input to the system, as shown in Figure 61, where the usual sensitivity oscillating pattern of the partially substituted electricity is also shown, around a mean value of 3.02E+15 J/yr, 70% lower than the 1.03E+16 J/yr of the I-BAU scenario in Figure 45 (due to the obvious consequences of the Carnot efficiency).

Figure 62 shows the decreased values of the total emergy U, respectively around 1.74E+22 sej/yr (-7% than I-BAU scenario) and 7.03E+21 sej/yr (-16% than I-BAU scenario), respectively with and without L&S.

In a like manner EYR, ELR, %REN and ESI were calculated (with and without L&S) and results are diagrammed as follows:

- Figure 63, EYR values with L&S (with a mean value of 1.05) and without L&S (with a mean value of 1.02);
- Figure 64, ELR values with L&S (with a mean value of 21.28) and without L&S (with a mean value of 43.11);
- Figure 65, %REN values with L&S (4.5% **–** mean value) and without L&S (2.3% **–** mean value);
- Figure 66: ESI values with and without L&S (respectively 0.049 and 0.024).

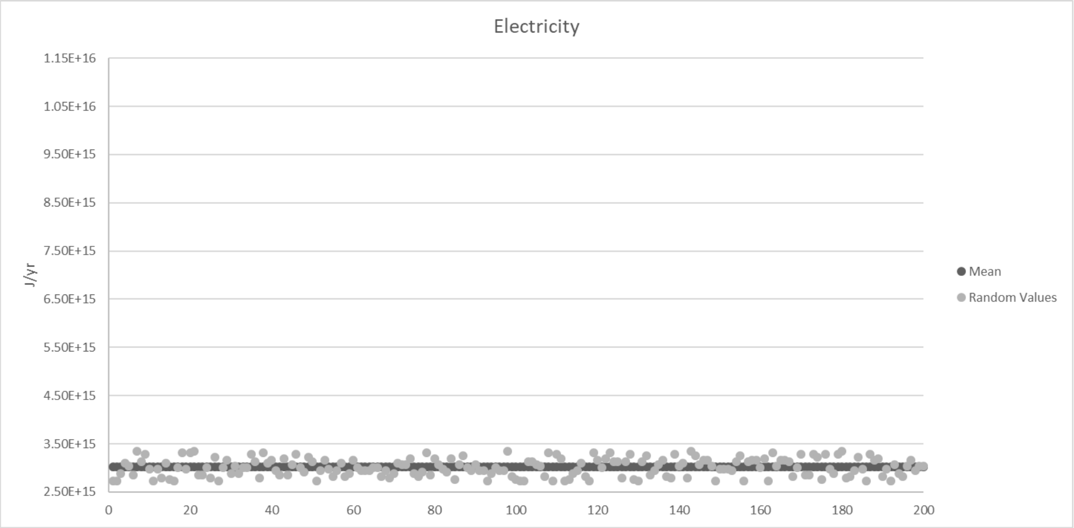


Figure 61 – Eco-Efficiency scenario: Improvement of hotspot flow.

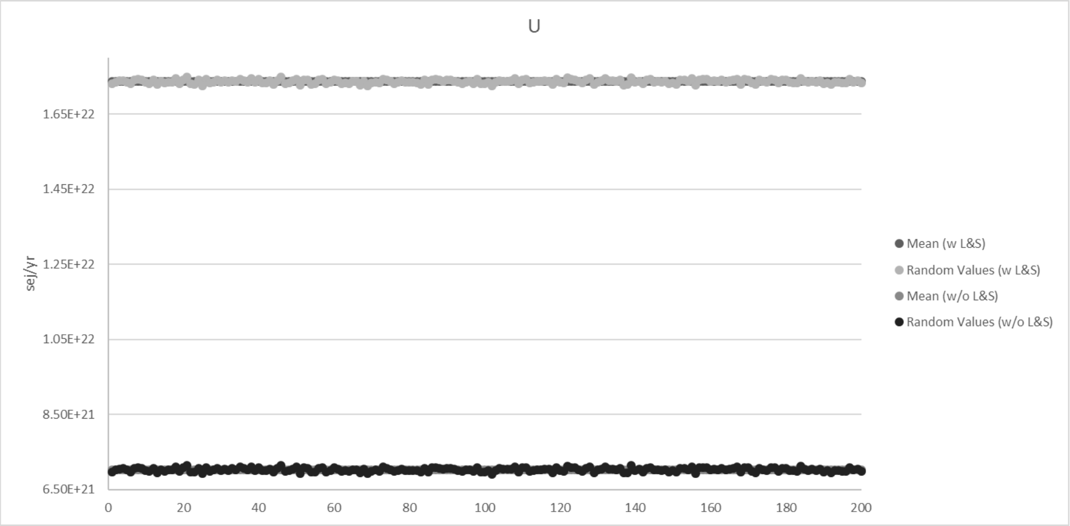


Figure 62 – Eco-Efficiency scenario: Total Emergy U with and without L&S

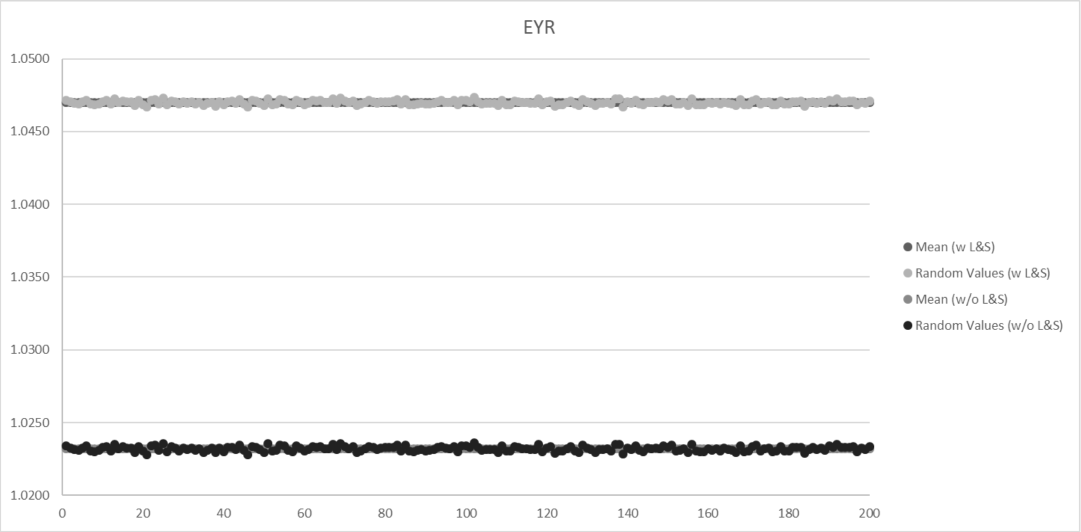


Figure 63 – Eco-Efficiency scenario: EYR with and without L&S

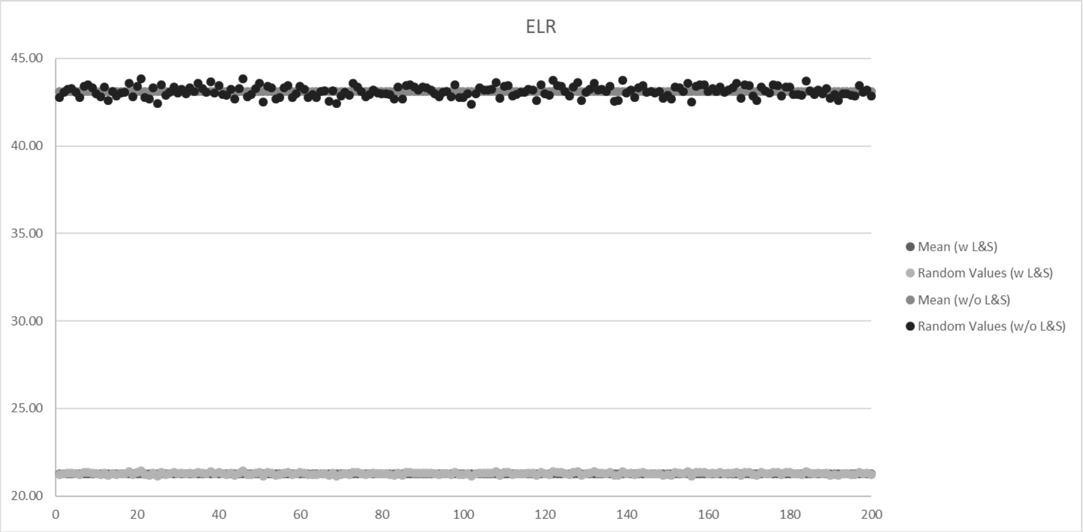


Figure 64 – Eco-Efficiency scenario: ELR with and without L&S

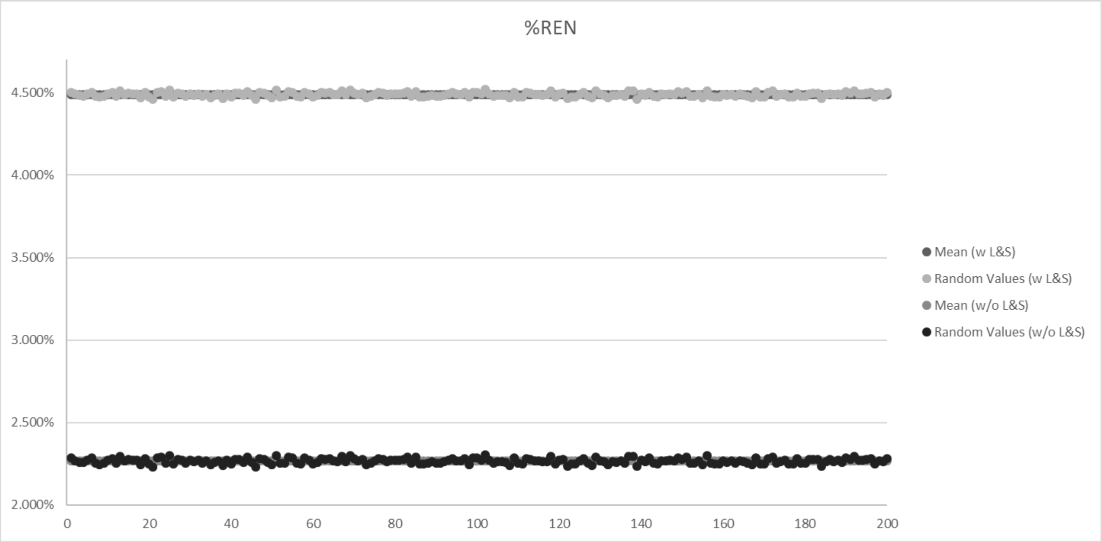


Figure 65 – Eco-Efficiency scenario: %Ren with and without L&S

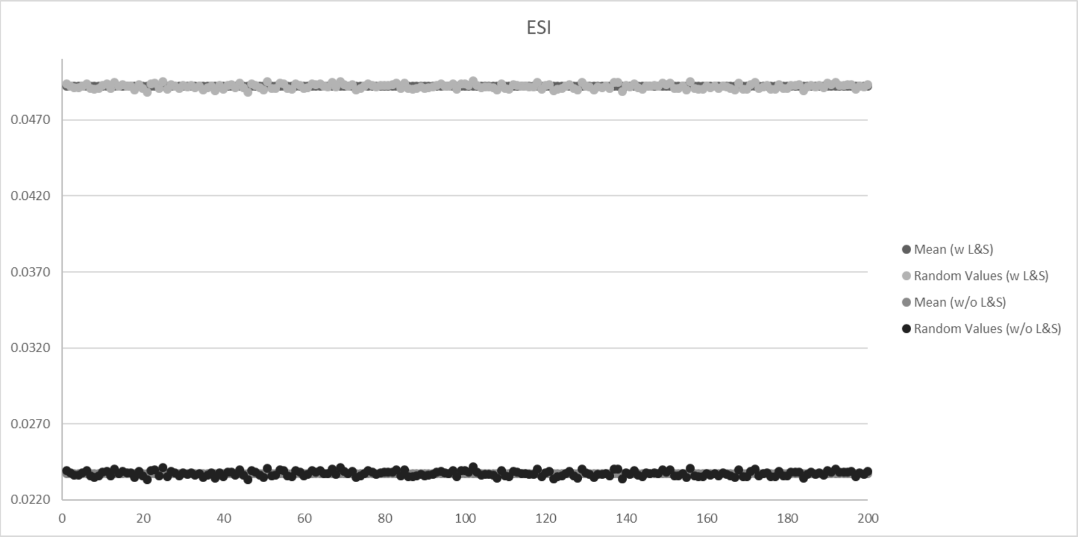


Figure 66 – Eco-Efficiency scenario: ESI with and without L&S

4.3 Concluding remarks

As with lower level cases investigated in previous Chapters, the analysis performed by applying the EUFORIE early prototype tool showed a better environmental performance within the Eco-Efficiency Implementation (EEI) scenario due to the higher improvement obtained thanks to the partial substitution of mainly fossil energy sources with renewable ones (in principle, substitution of sources characterized by high UEV with sources characterized by lower UEV, namely lower environmental cost). A further improvement could be obtained through the complete substitution of the nonrenewable energy sources. Moreover, simultaneous application of TEI and EEI strategies could lead to the implementation of very environmentally sound policies. It is very important to point out that a tool capable to generate quantitative performance indicators based on choices on the input side allows the discussion of policies based on facts instead of words, quantitative measures instead of ideological bias, possibility to choose intermediate or optimum solutions that take into account at least partially the requests of all stakeholders. This is impossible when there are no quantitative measures and scenarios on the discussion table.

Furthermore, we can conclude that the main findings carried out from the evaluation of the three scenarios developed within the system level analyzed are:

The crucial importance to carefully monitor the local and cumulative energy and resource use by cities as well as to realize that energy demand grows nonlinearly with urban systems' size;

The use of locally available resources (use of renewable energy and recycled materials) could produce positive consequences at local and global scales;

Overcoming mono-dimensional assessments (only assessing energy or specific material flows) would push policy-makers towards the possibility to deeper investigate a network of flows, merging different methods and suggesting effective and comprehensive sustainability policies.

Understanding which flows are the top contributors of the environmental support (i.e. which would convert into the largest emergy flows) helps 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.

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5. Appendix

5.1 An application of the MuSIASEM approach to an urban system (Barcelona)

Laura Pérez Sánchez, Maddalena Ripa, Raúl Velasco-Fernández, Gonzalo Gamboa, Renato F. Rallo, Mario Giampietro, 2017. *Energy performance at city level − the societal metabolism of Barcelona*. In: Book of Proceedings of the 10th Biennial International Workshop "Advances in Energy Studies", BIWAES, edited by S. Ulgiati and L. Vanoli, Napoli, September 25-28, 2017 Technical University of Graz Publisher - Pp. 772

5.2 A comparison of two urban systems (Napoli and Hongkong) via the MuSIASEM approach

Renato F. Rallo, Amalia Zucaro, 2019. *Assessing the Energy Metabolism of Urban Systems: A Comparison of Napoli and Hong Kong Through the MuSIASEM Approach*. Journal of Environmental Accounting and Management 7(2): 189-201

5.3 The SUMMA approach. Rationale, methodological aspects and results

Ulgiati, S., Ascione, M., Bargigli, S., Cherubini, F., Franzese, P.P., Raugei, M., Viglia, S., Zucaro, A., 2011. *Material, Energy and Environmental Performance of Technological and Social Systems under a Life Cycle Assessment Perspective*. Ecological Modelling, 222(1): 176-189.

From: Book of Proceedings of the 10th Biennial International Workshop
"Advances in Energy Studies", BIWAES, edited by S. Ulgiati and L. Vanoli, Napoli, September 25-28, 2017
Technical University of Graz Publisher - Pp. 772

Energy performance at city level − the societal metabolism of Barcelona

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Abstract

Cities are the engine of economic development but their dynamics need to be supported by the convergence of large flows of material and energy resources. According to the UN World Urbanization Prospects (2014), 54% of the world's population resided in urban areas in 2014, and this figure is expected to reach 66% by 2050. Although cities presently cover less than 2% of the earth's surface, they consume about 78% of the energy under human control, to which one must add the amount of material products (food, building materials, metals, etc.) that indirectly require energy consumption. Many cities have pushed out their industries to their metropolitan areas or to remotest regions becoming basically services cities. Many infrastructures shape and characterize the urban metabolism, as well as the mix of service activities taking place inside the city or the heterogeneous residential sector within the city. Even more challenging is the fact that many activities of a city are carried on by people (commuters, tourists) that do not live in it. This fact poses an epistemological challenge when coming to defining the boundaries to be considered for metabolic analysis (who is consuming energy to do what). In the present paper we present an innovative analysis of Barcelona energy metabolism, a global city characterized by the importance of its service sector, especially for tourism. For this analysis, we use the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), an innovative tool capable of analyzing biophysical flows/fund relations by characterizing the energy metabolic pattern of the different functional sectors and neighborhoods of the city. The tool can be used both in diagnostic mode or simulation mode to have a better informed discussion about hot topics such as energy efficiency, energy poverty, energy transition, or energy democracy. This study was developed as part of a broader project Euforie (European Futures for Energy Efficiency), founded by EU in 2015, with the goal of developing a tool capable of characterizing how different forms of energy carriers are used to perform different societal tasks – i.e. end-uses - (industrial production, mobility, tourism, residential, commercial activities, etc.). The proposed approach allows looking for potential conflicts among these end-uses in the case drastic measures of de-carbonization may limit the supply of the required energy inputs.

1. Introduction

Cities are the centre of the economy and power of nations. In 2014, 54% of the world population was reported to live in urban areas and, according to UN projections, it could reach 66% by 2050 (United Nations, 2016). Cities are the places where higher value added activities are developed, already accounting for 80% of the world's GDP in 2013 (OECD 2016). Cities are socio-ecological systems – SES - (Odum, 1971; Rosen, 1991; Tainter, 1988) that are in constant evolution and interact with their smaller parts and the external systems in a nowadays worldwide network. From a thermodynamic perspective, cities represent open systems, constantly importing and exporting energy and matter across their boundaries (Nicolis and Pricogine, 1977).
Globalization highlights the openness of urban systems: choosing between domestic and foreign products, living with foreign neighbours or looking for a job abroad, exchanges of information through communication technologies. Fossil-fueled transport and the more recent advances on telecommunications have created a globalized and international division of labor and reshaped cities worldwide. Nicolis and Prigogine (1977) noted that a city "can survive as long as it is the inflow of food, fuel and other commodities and sends out products and waste", and cities are increasingly bringing

these inputs from further so they can devote their human capital to other activities. In fact, the maximum economic power is represented by a group of global cities with transnational corporate headquarters, finance and IT centres, news offices, information and entertainment services, and Barcelona is considered one of them (Sassen, 2010). Also, these increased mobility options make that many activities of a city are carried on by people (commuters, tourists) that do not live in it. This fact poses an epistemological challenge when coming to defining the boundaries to be considered for metabolic analysis (who is consuming energy to do what).

At an urban level, the industrial revolution and the modernism in urbanism have enhanced the plurality of functions that a city can perform, generating areas devoted to different and single activities (López de Lucio, 1993). The city, then, works as a conglomeration of organs that have been adapted to perform a specific function and that, interacting, create an emergent property ("the whole is greater than the sum of its parts") (Von Bertalanffy, 1972).

Thus, as living organisms, cities have metabolism. The "metabolism of human society" is a notion used to characterize the processes of energy and material transformation in a society that are necessary for its continued existence. This notion became a scientific subject starting the mid-19th century because of the work of authors such as Liebig, Boussingault, Moleschott, Jevons, Podolinski, Arrhenius, Ostwald, Lotka, White, and Cottrel (for an overview, see (Martinez-Alier, 1987)).

The proper accounting of urban metabolism is of paramount importance when policy plans aiming at energy efficiency and climate mitigations strategies (e.g. PMEB - Barcelona Energy Improvement Plan , PECQ, - Pla d'Energia Canvi Climàtic i Qualitat de l'Aire de Barcelona (Ajuntament de Barcelona, 2011), COM, Covenant of Mayors performance) come into play.

The analysis of the metabolic pattern of a social-ecological system has to be first framed in semantic terms and then formalized in quantitative assessments using an integrated set of metrics (different categories of accounting). Therefore, the analysis of the metabolic pattern has to start with the identification of the metabolic characteristics of its functional elements and their forced relations. To understand better this task let's start from the definition of "a system" and apply to this definition the wisdom of relational analysis.

A system is a set of functional and structural components linked by some form of interaction and interdependence operating within a given boundary ***to achieve a common final goal*** *(a given final cause)*.

The final cause of a complex system, as a city, is the "emergent property" of the system: it is what makes "the whole" meaningful and more than the sum of its parts. In the case of an analysis of urban metabolism the emergent property of a city is its ability of reproducing, maintaining and adapting its identity in time. Adopting an impredicative definition – typical of self-producing and adaptive systems – we can say that the identity of the city is associated with the ability to preserve and adapt the meaning of the identity of the set of functional and structural elements composing it.

The narrative of urban metabolism – the integrated set of material and energy flows that have to be metabolized to preserve and adapt the identity of the city - can be used to provide the rationale for: (i) identifying the functional and structural parts of the metabolic pattern; and (ii) studying the relations over them.

***A city** is composed by a set of functional and structural components **operating in the technosphere** (processes under human control) within a prescribed boundary. The goal of a city is that of reproducing and maintaining its identity (the identity of the whole) while learning how to become more adaptable. The functional components of a city are linked through a pattern of expected interactions determining a dynamic interdependence over their identities (defined at hierarchical level lower than the one of the city). The possibility of stabilizing the metabolic flows consumed and generated by a city depends on the existence of other processes **operating in the biosphere** (processes outside human control) determining the required supply and sink capacity.*

Therefore, in this paper, MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) is used to analyze the urban metabolism in Barcelona by identifying across different hierarchical levels of organization: (i) the whole with its boundary; (ii) the functional compartments; (iii) the functional elements of the functional compartments; (iv) the structural elements operating in the functional elements, that can be used as external referent to study their metabolic characteristics.

2. Materials and Methods

2.1. MuSIASEM framework

The Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) (Giampietro, 2003; Giampietro et al., 2013, 2012, 2009, 2006, Giampietro and Mayumi, 2000a, 2000b, 1997; Giampietro and Sorman, 2012; Pastore et al., 2000; Ramos-Martin et al., 2007; Sorman and Giampietro, 2011) is a quantitative tool to analyze socio-economic systems using simultaneously technical, economic, social, demographic and ecological variables. MuSIASEM builds on the flow-fund model of Georgescu-Roegen (1971) as well as on complexity theory and autopoietic systems theory (Maturana and Varela, 1998, 1980, Ulanowicz, 1997, 1986).

In order to define the metabolic pattern of human societies we must define "what the system is" and "what the system does", which Georgescu-Roegen (1975) defined as fund and flow elements, respectively. Funds (capital, labor, available land) are agents that enter and exit the process, transforming input flows into output flows. They preserve their identity over the given period of analysis and must be periodically renewed, and the maintenance of these funds is the basis of sustainability. Flows (energy, products, money) are elements that enter but do not exit the production process, or that exit without entering. Flows and funds are related: the sizes of the various flows are determined by the characteristics of the various processes taking place inside society and, in turn, these processes are determined by the combination of the size and the metabolic characteristics of the fund elements metabolizing the flows. Thus, at a practical level, any flow of energy (a quantity per year in MJ or kWh) must always be associated with the size of a fund element (a structural element used as external referent as hours of human activity or m^2 of land use), in order to have the metabolic characteristic of the fund element: the pace (MJ/h) or the density (MJ/ m^2).

The link between a quantity of energy consumed and the metabolic process associated is important because it establishes an accounting scheme across different hierarchical levels. These ratios can be compared between levels or also against reference values (benchmarks) describing known types of socio-economic systems. The information on extensive variables comes from statistical sources (top-down), whereas the one on the paces or densities are available as technical characteristics of structural elements (bottom-up). The parallel use of these two sources of information generates redundancy in the information space (the so-called Sudoku effect (Giampietro and Bukkens, 2015)) which allows triangulating. Each hierarchical level (shown in Figure 3) is described by an array of intensive and extensive variables defined in relation to quantities calculated on a year basis as in the following:

Ext. var.		Intensive variables								Extensive variables			
HA	**BU**	**EMR_{elec}**	**EMR_{heat}**	**EMR_{fuel}**	**EJP**	**EMD_{elec}**	**EMD_{heat}**	**EMD_{fuel}**	**EBUP**	**ET_{elec}**	**ET_{heat}**	**ET_{fuel}**	**VA**
Funds		Flow/Fund								Flow			

Where:

Table 1: Indicators used in the MuSIASEM of Barcelona
(intensive variables are averages per year)

Indicator		**Definition**	**Unit**
HA	Human Activity	time invested in the end-use per year	h per year
BU	Building Use	quantity of area devoted to the end-use	m^2
EMR_i	Exosomatic Metabolic Rate	ET_i/HA: amount of energy carrier *i* metabolized per hour of work allocated to the end-use	kWh/h or MJ/h
EJP	Economic Job Productivity	VA/HA: value added per hour of working time of end-use	€/h
EMD_i	Energy Metabolic Density	ET_i/BU: amount of energy carrier *i* metabolized per m^2 of building area devoted to the end-use	kWh/m^2 or MJ/m^2
EBUP	Economic Building Use Productivity	GVA/BU: value added per area of end-use	€/m^2
ET_i	Energy Throughput	Amount of energy throughput metabolized in the form of energy carrier *i* (electricity, heat or fuel) by the end-use.	kWh or MJ per year
VA	Value Added	Value Added of goods and services produced by the end-use	€/year

2.2 System description

Barcelona is the second biggest city in Spain and capital of Catalonia, located at the north-east of the Iberian Peninsula, limited at the east by the Mediterranean Sea and at west by the Collserola Mountain. With a population of 1,604,555 inhabitants in 2012 and occupying 102.16 km^2, it is one of the densest cities in Europe. It is divided in 10 administrative districts and 73 quarters ("barrios") (Ajuntament de Barcelona, 2012). The demographic structure of the city is the typical for a developed country (Figure 1), with an ageing population and an important flux of immigrants since the 1990s. Representing a 21.2% of the population and a 34.6% of the GDP of Catalunya, it is the center of a bigger metropolitan area (AMB) with some administrative functions, most of its population living in the urban agglomeration around Barcelona. The AMB had 3.299.337 inhabitants in 2012, and an important number of them commute every day from and to Barcelona (Àrea Metropolitana de Barcelona, 2012). Commuting takes place not only by car, since the city offers a wide supply of public transport (buses, metro, tram, traint, etc), connecting the different municipalities in the AMB to the city through a radial infrastructure.

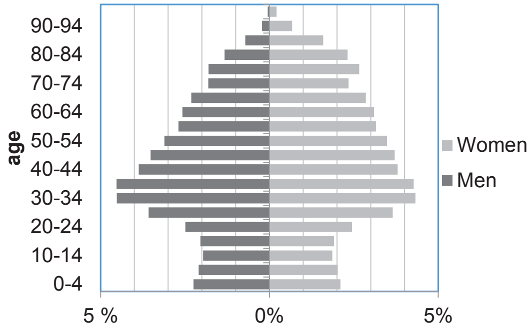

Figure 1: Demographic structure of Barcelona, 2012

2.3 Hierarchical organization of relevant economic sectors and subsectors

The boundary chosen for this study was the physical limits of the city including all the activities happening inside. The choice of the set of compartments is flexible; compartments may be aggregated or further disaggregated depending on the issue of interest, provided that the closure requirement is observed – i.e. the sum of the size of lower level compartments must sum up to the size of higher level the compartments. The hierarchical organization of the system of Barcelona is shown in Figure 2. First of all, the city of Barcelona (level n) is divided into two functional compartments (level n-1): paid work (PW), which generates value added, and the household sector (HH), reproducing individuals. n-2 inside HH we have two parts: residential (RES) (what happens inside the households) and private transport (MOB) (motorized private transport used outside of the paid work). The residential sector is further divided at n-3 level in the ten districts and at n-4 in the 73 “barrios”. At the level n-3 inside mobility there are two structural elements: cars and motorbikes.

It is important to note that the definition of functional elements is necessary to identify how to account the flows of energy metabolized by the structural elements. People living in residential buildings, vehicles moving in Barcelona, shops, installations and cruisers in the port, etc. (structural elements of Barcelona) are the external referents for the assessments of energy metabolism – they define the pace or the density of energy flows. Then the trip of a given model of a car – the external referent for fuel consumption – can be accounted in the household sector, if the car is used by a private or in the service sector if it is used as a taxi. The same criterion applies for the electricity consumed by an air-conditioner when used in a house or in an office.

Within the paid work sector two large sub-sectors and two functional elements are considered: Services and Government (SG), Manufacturing and Construction(MC), the port and the Energy Sector (ES). As the agricultural primary sector is negligible in the economy of the city, it is not considered. The port is included at the level n-2 due to its special key function: connecting the city at a global scale with the imports of energy, food and other products, and the exports of some manufactured products from the local industry.

Inside SG at the level n-3, there are activities related with transport, and sub-sectors (commerce, offices, education, healthcare, hotels bars and restaurants, and other) which at the level n-4 are organized by barrios.

Further details regarding the calculation procedures will be provided in the full paper.

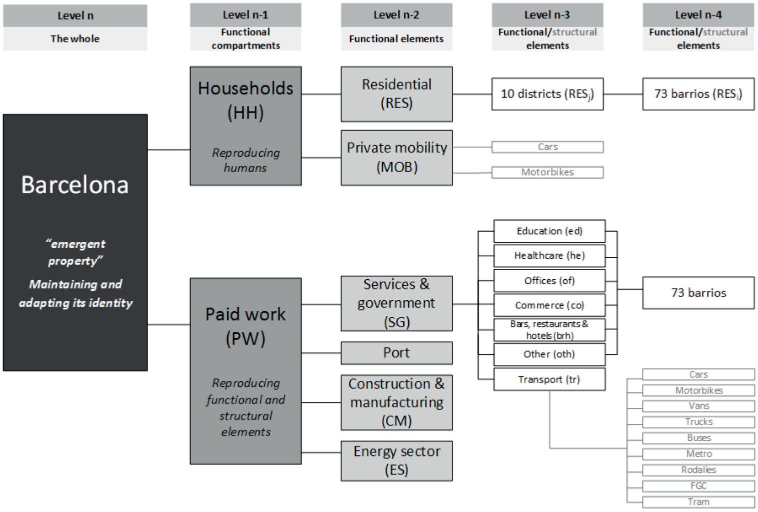

Figure 2: Hierarchical organization of relations over functional and structural elements for the accounting of metabolic flows in Barcelona.

3. Results and Discussion

The results of the analysis are here summarized in two tables. Due to the limitation of space, the results of levels n-3 and level n-4 are not shown here. Nonetheless, they will be reported in the full paper.

3.1 Level n, n-1, n-2

Table 2 shows the array of values (extensive and intensive) expressing the flows of energy carriers (electricity, heat and fuel) and value added produced by the different hierarchical (functional) compartments of the city, whose size is determined by the HA (i.e. human time). Table 3 presents the array of values (extensive and intensive) expressing the flows of energy carriers (electricity, heat and fuel) and value added metabolized by the different hierarchical (functional) compartments of the city, which are here sized depending on the building area in use (BU).

In both tables, each level can be described using extensive variables – the quantity of either fund and flow elements averaged over a year, representing their "size" - or intensive variables (expressed as the ratios between flows and funds, e.g. kWh/h), expressing the pace and density.

The BCN level (city), our focal level (n), accounts for the total amount of flows consumed by society and the total funds that have to be reproduced in a city. As already shown in previous analyses, HA in HH represents around 90% of total HA. The largest share of HA_{PW} is allocated to the SG sector, which has the largest metabolic ratios (EMD_{el} and EMR_{el}) for electricity and the lowest for heat. In developed countries, the household sector (human activities outside of paid work) and the services sector (private and public services) are considered as net consumers of biophysical flows (i.e. bio-economic pressure), which must be supplied by the primary and secondary sectors. The energy sector has especially high metabolic ratios, and at the same time, a low HA and BU. This is in line with the fact that in Barcelona has only one power plant within its boundaries contributing only partially to the electricity supply of the city. Apart from this traditional classification of sub-sectors there's the port, which has a special behaviour, with high EMRs and EJP but at the same time lower EMDs and EBUP than the other sectors in PW. These values can be explained by the use of large machinery and ships, the little work associated to it and the need of space to store and move the goods. The existence of this infrastructure is neither significant only in monetary terms, since it is the piece of the system that allows international shipping both for exports and imports of energy, food and products whose production has been externalized, nor from a city perspective, since it provides services to the whole hinterland.

Table 2: End-use matrix, including EMRs and EJP, of the main levels of analysis (n, n-1, n-2) in Barcelona, 2012

	HA	**EMRs**			**EJP**	**ETs**			**VA**
		Elect.	**Heat**	**Fuels**		**Elect.**	**Heat**	**Fuels**	
	Mh	kWh/h	MJ/h	MJ/h	€/h	GWh	GJ	GJ	M€
(n) BCN	10929	0.7	2.4	1.4	5.6	7,139	26,697	15,765	61,527
(n-1) HH	9328	0.3	0.3	0.7	0.0	2,341	2,572	6,626	0
(n-2) RES	9209	0.3	0.3	0.0	0.0	2,341	2,572	0	0
(n-2) MOB	119	0.0	0.0	55.7	0.0	0	0	6,626	0
(n-1) PW	1601	3.0	15.1	5.7	38.4	4,798	24,125	9,138	61,527
(n-2) SG	1410	3.0	2.8	4.6	38.0	4,161	3,990	6,492	53,527
(n-2) PORT	18	10.8	66.7	148.7	81.5	192	1,187	2,647	1,450
(n-2) MC	168	2.3	42.6	0.0	35.4	385	7,176	0	5,954
(n-2) ES	4	14.3	2814.4	0.0	142.3	60	11,772	0	595

Table 3: End-use matrix, including EMDs and EBUP, of the main levels of analysis (n, n-1, n-2) in Barcelona, 2012

	BU	**EMDs**			**EBUP**	**ETs**			**VA**
		Elect.	**Heat**	**Fuels**		**Elect.**	**Heat**	**Fuels**	
	km^2	kWh/m^2	MJ/m^2	MJ/m^2	€/m^2	GWh	PJ	PJ	M€
(n) BCN	118.2	60.0	225.8	133.0	521	7,139	26,697	15,765	61,527
(n-1) HH	62.3	37.6	41.3	106.4	0	2,341	2,572	6,626	0
(n-2) RES	51.8	45.2	49.7	0.0	0	2,341	2,572	0	0
(n-2) MOB	10.5	0.0	0.0	629	0	0	0	6,626	0
(n-1) PW	55.9	85.8	431.5	163	1101	4,798	24,125	9,138	61,527
(n-2) SG	37.1	112	107.6	175	1443	4,161	3,990	6,492	53,527
(n-2) PORT	8.3	23.2	143.2	319	175	192	1,187	2,647	1,450
(n-2) MC	10.5	36.6	681.6	0.0	566	385	7,176	0	5,954
(n-2) ES	0.04	1,655	324,656	0.0	16420	60	11,772	0	595

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Assessing the Energy Metabolism of Urban Systems: A Comparison of Napoli and Hong Kong Through the MuSIASEM Approach

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Abstract

Urbanization, that is the expansion of cities and the emptying of the countryside, has been the trend of the last decades and does not seem to stop. In light of this phenomenon, quantitatively analyzing cities through shared and standardized methods has become a scientific urgency. Nevertheless, the efforts made so far have proved to be insufficient, and a science of cities is still far from being constituted. In this paper we present a first attempt to evaluate the energy metabolism of Napoli and Hong Kong through the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) and its End-Use Matrix, that is connecting produced and consumed flows to their users. The comparative analysis provides interesting results and potentially allows for useful policy recommendations.

1 Introduction

1.1 Why cities?

Cities are one of the key aggregation levels to analyze the reality of these years. The United Nations estimates that the urban population was 54.5% in 2016 (United Nations, 2016), having passed the threshold of 50% in 2007. Furthermore, cities already accounted for 80% of the world's GDP in 2013, 78% of the energy available on the planet, to which one must add the energy required for the production of material goods (food, building materials, metals, etc.), and 70% of total energy-related CO_2 emissions (IEA, 2016; Viglia *et al.*, 2017). In Europe, 72.4% of citizens live today in cities.

This wave of mass urbanization represents a positive or negative opportunity, depending on the environment in which it is carried out, and how it is managed and planned. Especially in developing countries, too fast and uncontrolled urbanization rates can lead to serious problems (e.g. slum formation, unequal distribution of spaces and resources across the city, environmental pollution (Zhao *et al.*, 2013). Understanding the dynamics of the city is therefore one of the most challenging and urgent needs of this era. Various attempts in

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this regard are made at the academic level (Batty, 2008, 2012), (Bettencourt *et al.*, 2007; Bettencourt, 2013), to intercept common trends and develop effective policy tools for more sustainable city design.

1.2 Why urban sustainability?

Covering less than 3% of the Earth's surface, and consuming more than ¾ of resources available, cities' sustainability is hard to define in a meaningful way. More specifically, a city behaves as a living organism, that is it feeds on resources outside its bio-physical boundaries, and in turn provides its surrounding services of all kinds: education, security, social life, transportation, opportunities for business. Supporting these activities requires significant flows of resources, resulting in an environmental stress both locally and globally.

Trying to establish a lasting balance between the city and its surroundings is one of the goals of this research. The sustainability of this balance depends on external constraints, specifically the availability of resources. Among the various factors, mass urbanization has been the result of a strongly globalized economy organization, based on the growing use of fossil energy sources. Nowadays, cities depend overwhelmingly on fossil fuel-powered machinery for the extraction of raw materials for manufacturing (almost all of which occurs in or near cities), or for moving goods and people from home, work, shopping, school, leisure activities; for importing food and exporting wastes of all kinds. Fossil fuels boosted and replaced human labor in every production sector, increasing efficiency through continuous innovation in technology. Yet, in an era of great concern about the availability of resources, the diminishing return on investment to extract them, and its growing side effects on the environment, it is even more important to reassess a sound equilibrium between urban and rural environment.

1.3 What is urban metabolism?

Urban metabolism is a metaphor used to analyze the dynamics of a city as if it were a living organism: the city takes resources from its surroundings and returns waste with a high level of entropy. Abel Wolman (Wolman, 1965) was the first to develop the concept of urban metabolism (UM), in a paper where he imagined the functioning of an hypothetical city of 1 million people, evaluating its consumptions. Along the decades, urban metabolism fairly diffused in scientific literature and is widely defined as the sum of the technical and socioeconomic processes that occur in cities, resulting in resource consumption, growth, production of energy and elimination of waste (Kennedy, Cuddihy and Engel-Yan, 2007).

Adopting the idea of a natural ecosystem and applying it to an urban environment is agreed to be a good way to frame urban sustainability, because both natural and anthropic systems rely on bio-physical factors. Natural ecosystems are generally energy self-sufficient, and regulate themselves according to their surroundings developing a closed loop metabolism. Contemporary cities, conversely, have highly linear patterns of consumption, both of energy and materials.

On urban metabolism several studies have been done over the years. The main strands on which this type of study has been divided are two: on the one hand, the 'emergy' school of Odum, which seeks to bring the various streams back to an energy equivalent, e.g. (Viglia *et al.*, 2017); on the other hand, studies based on Material Flow Accounting (Fischer-Kowalski *et al.*, 2011) consider the flow of raw materials, water and air in terms of mass. However, the novelty of these methods has not yet reached a standard classification system for stocks and flows in urban metabolism, as outlined in the Urban Metabolism workshop held by industrial ecologists at MIT in January 2010.

Regarding the energy metabolism of cities, a vast analysis of the consumption of megacities (cities with more than 10^7 inhabitants) in the world was conducted by Facchini et al. (Facchini *et al.*, 2017). In the comparison of the values, the authors find that per capita energy consumption scales with urban population density according to a power law with exponent -0.75: this means that the more densely populated is a city, the lower its per capita energy consumption will be. For a broader outlook of urban metabolic studies, see (Weisz and Steinberger, 2010; Kennedy, Pincetl and Bunje, 2011; Hoornweg, Campillo and Linders, 2012).

As for the usefulness of urban metabolism's assessment, (Kennedy, Pincetl and Bunje, 2011) states that it is often an exercise of accounting, but beyond that, it could be used as a basis for sustainable urban design and policy analysis. As described by (Pincetl and Bunje, 2009), the main advantages of using UM as a unifying framework to study sustainable urban development are it allows for hierarchical approach to research, includes decomposable elements for sectorial insights and integrates social and biophysical elements. On the other hand, being a relatively new assessment method, it still lacks some standardization. The most urgent question is possibly the one concerning urban boundaries: as pointed out by many authors, e.g. United Nations (United Nations, 2016), there is no agreement on which geographical boundaries are to be considered most relevant in such analyses. One definition, sometimes referred to as the "city proper", takes into account the inner administrative boundary. A second approach, termed "urban agglomeration", also considers the contiguous urban area, or built-up area. Finally, some refer to the whole "metropolitan area", including in its boundaries the economically and socially interconnected contiguous areas, characterized by frequent commerce or commuting patterns with the metropolis (for a more complete discussion on urban boundaries, (Potere and Schneider, 2007; Fang and Yu, 2017)).

The aim of the study is to evaluate the energy metabolism of two very different cities, Napoli (Italy) and Hong Kong (China), using the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), a multicriteria approach capable of dealing with the complexity of a territorial energy system. MuSIASEM, which will be explained in greater detail in the next paragraph, is based on the theory of complex systems and on the concepts of flow and fund, as developed by Georgescu-Roegen (Georgescu-Roegen, 1971, 1975). The goal of such comparative analysis is, given the "qualitative" differences of the two cities (size, main economic sectors, culture, etc.): do the indicators reflect these differences in a quantitative way? Where, instead, this does not happen, and why? In order to answer to these questions the present paper is organized as follows: (i) in the first part the presentation of the MuSIASEM methodology is carried out; (ii) secondly, a brief description of Napoli and Hong Kong, contextualizing economic and social aspects, and the respective energy policy frameworks are reported, and (iii) finally the results of the application of MuSIASEM to the energy metabolism of the two investigated cities are presented and discussed, identifying the future steps to make in this line of research.

2 Method

This study applied the End-Use Matrix tool, conceived in the frame of the MuSIASEM approach, to characterize the metabolism of the two cities considered. In accordance with the epistemological premises of MuSIASEM, the end-use matrix makes it possible to relate fluxes and funds, and thus generate indicators relevant and coherent from a theoretical point of view. The merit of this type of approach is to always provide a solid reference to the qualitative and quantitative assessment of flows, that is to link them to the reproduction of funds. Analyzing only the flows, untying them from the subjects that exploit them and from the final ends that move them, bears the risk to provide an oversimplified image of the system. The attempt of MuSIASEM then is to recreate this link, through a more complex but also more complete evaluation, that might turn out to be more useful to policy makers.

Another fundamental characteristic of MuSIASEM grammar is that, as previously theorized by Georgescu-Roegen (Georgescu-Roegen, 1975), it considers human society as relying on two distinct forms of metabolism: (1) an endosomatic one – e.g. food, energy and other material flows metabolized inside the human body for preserving and sustaining the physiological activity of humans; and (2) an exosomatic metabolism – e.g. energy and other material flows converted outside the human body with the goal of boosting the efficacy of human activity (e.g. when using tractors, melting metals, moving heavy loads or refrigerating food). For more details about the method, please refer to Giampietro et al. (Giampietro and Mayumi, 2000; Giampietro *et al.*, 2014). Recent examples of this approach are presented in Kovacic et al. (Kovacic and Giampietro, 2017), which assesses the policy challenges of informal settlements, and in Ramos-Martín et al. (Ramos-Martín *et al.*, 2009) and Sánchez et al. (Sánchez *et al.*, 2017) which analyse the energy metabolic pattern of Catalunia region and Barcelona, respectively.

In the case studies investigated in this work, 4 variables, 2 funds and 2 flows are identified.

The funds are 1) total time (hours) of human activity (HA), including all people that play a role in the urban life, and 2) the total area of the system (squared km) (land use - LU). This last value is assessed at ground-floor level, except for the case of the residential sector, where multi-storey internal area data were available.

The flows are 1) Energy Throughput (ET), that is the final energy consumption unpacked in three different types (electricity, natural gas, liquid fuels), and 2) economic Value Added (VA), expressed in Euro. (All prices in HK$ have been converted to € as the exchange rate of 31/12/2012, which is the date considered also for prices in €).

From the crossover of these extensive variables, in particular - as expressed above - by linking the flows to the funds, four intensive indicators are generated:

1. **EMR -** Exosomatic Metabolic Rate: ET/HA, the amount of each energy carrier used per hour
2. **EJP** – Economic Job Productivity: VA/HA, the value added per hour of Paid Work
3. **EMD** – Exosomatic Metabolic Density: ET/LU, the amount of energy carrier per unit of area
4. **ELUP** – Economic Land Use Productivity: VA/LU, the value added per unit of area.

These intensive indicators allow us to make performance comparisons within the system, for example between different sectors, or with other cities.

In the present study we make the following assumptions:

- The geographical fund taken into account is the area within the boundary of the administrative city;
- The human fund considered is the resident population plus tourists & visitors plus commuters. This choice was due to the fact that tourists and commuters contribute notably to the economy and operation of the urban life.
- Everyone spends half of their free time at home, and the other half in the use of services.
- Incoming commuters are divided equally between workers and students. The average 9 hours spent inside the city boundaries are allocated as follows: 8 hours are used for the main activity (work or study, respectively) and 1 hour is spent for services (e.g., restaurant).
- In the case of Napoli, due to the lack of suitable statistical data about economic Added Value at the city level, province level data were adjusted, according to the following equation:

$$€_{sector\ i,city} = \frac{employees_{sector\ i,city}}{employees_{sector\ i,province}} * €_{sector\ i,province} \tag{1}$$

The human activity is divided into two macro categories: Paid Work (PW), to express paid activities, and the Outside Paid Work (OPW), to express all other activities (including the use, as a user, of services for which the provider is paid). This separation is necessary to avoid double-counting problems. Time spent at home, for mobility and for the use of services (‘Use of S&G’, as for example time spent in a restaurant or in a medical centre) is part of the OPW. The Paid Work is instead divided, where statistical data are available, in the categories of Agriculture, Energy, Construction & Manufacturing (C&M), Services & Government (S&G). The latter, not to be confused with the ‘Use of S&G’, accounts for the supply of services, and includes Offices, Education, Healthcare, Commerce, Bars / Restaurants / Hotels are also evaluated.

3 Case studies: Napoli and Hong Kong

3.1 An introduction of Napoli

Napoli is the largest city in Southern Italy and one of the most important economies in the whole country. In the year considered for the present analysis, 2012, Napoli had a population of 962,003 inhabitants. The tourist visits amounted to $2.3 \cdot 10^6$ nights / year. On the other hand, the daily commuters were 275,000 inbound and 194,000 outgoing, hence a net figure of 81,000 incoming commuters.

The area considered is the municipal area, and equals 119 sq. km.

Napoli has an artistic heritage, both material and immaterial, which is world-renowned, from culinary tradition to music and theatre art. From a geographical point of view, it overlooks the Gulf of Napoli in the Tyrrhenian Sea. The privileged access to the sea has always characterized its cultural and economic identity. Napoli is in fact home to a large port, which is still an important commercial spot for the national trade. Together with its hinterland, Napoli had an important industrial development, hosting among others the Fiat factory of Pomigliano d'Arco, the Italsider in Bagnoli (which was closed in 1990) and the historic shipyards of Castellammare di Stabia. Nevertheless, the tertiary sector remains the most important economic sector. In the '90s the city has, first in Southern Europe, equipped itself with a cluster of skyscrapers to be dedicated to services, giving it the name of Centro Direzionale. Among the services, tourism has held a central role, reaching top numbers in the last decade.

As for the energy supply, within the municipality of Napoli there is only one combined cycle thermoelectric power plant, which, by burning natural gas, can supply 400 MWe of power. In 2012, it provided the city with 1412 GWh of electricity, while in the same year the electricity consumed by Napoli was roughly twice that amount, that is 2752 GWh.

3.2 Napoli Energy Policy framework

In the energy field, the European target is to reach, by 2030, -40% of carbon emissions (compared to 1990), 27% of energy coming from renewable sources and 27% of energy savings from improved efficiency. (European Commission, 2014) As for the carbon market, there is an Emission Trading System that includes aviation, manufacturing and energy sectors. These are estimated to account for 45% of EU total emissions (European Union, 2007a).

At the level of cities, the European plan on climate change - launched in 2007 (European Union, 2007b) - was followed one year later by the Covenant of Mayors (European Union, 2008). This is a platform that cities of all sizes can voluntarily join, committing to support the EU 20-20-20 strategy, especially regarding emissions. Mayors that adhere to the platform (Napoli has adhered in May 2009) are asked, within the following year, to prepare a Baseline Emission Inventory, submit a Sustainable Energy Action Plan with concrete measures to pursue the goal, and keep monitoring progresses along the process.

3.3 An introduction of Hong Kong

Hong Kong is one of the key cities of the global economy, straddling South East Asia and China (to which it belongs). In the year 2012 it had a population of 7,154,600 people. The tourist visits in the same year amounted to 84×10^6 nights / year, plus 24×10^6 daily visitors / year. The city is located on an area of 1,104 km^2. Hong Kong has a particularly complex history, mainly due to its extremely strategic geographic position. At the mouth of the Pearl River, its port (now called Victoria Harbor) was the natural crossroads of trade between India, China and Europe (whose main actors were United Kingdom and Portugal). After the First Opium War (1839 - 1842) it was ceded to the United Kingdom with the Treaty of Nanking (29 August 1842). In 1997, after 155 years of British rule, Hong Kong was transferred to China, within which today it represents a special administrative region. This historical alternation is also reflected in the cultural blend present in Hong Kong, where the mix between the Chinese tradition and some aspects of the social and economic life of the city is still vivid.

The Hong Kong's economy is focused on the tertiary sector, this accounting for roughly 93% of the GDP. Financial services and trade are the main tertiary activities. In both sectors, the strength of the city has been to act as a link between mainland China and foreign capital, especially after the Chinese economy was liberalized in 1978. Mainland liberalization has also pushed the competition with many other Chinese commercial cities, though, but Hong Kong has remained very attractive for foreign companies. Among the various aspects, low taxation, common law system (Parliament of United Kingdom, 2015), and great economic freedom are the main levers to convince companies to establish their Asian headquarters on the island. This great economic activity is reflected in a large energy consumption. On the transport level, the city has an excellent public service, with rates of use by the population among the highest in the world (Transport and Housing Bureau, 2017). As for the electricity supply Hong Kong has four power stations: Black Point (gas), Castle Peak (coal), Lamma (coal), Penny's Bay (diesel). Together with the only industrial size wind turbines, Lamma Winds, they provide 77% of Hong Kong electricity. The remaining part is imported from mainland China.

3.4 Hong Kong Energy Policy Framework

The main local framework for energy policy is Hong Kong’s Climate Action Plan 2030+ (Environment Bureau, 2017). Produced after the resonant UN COP21, which took place in Paris in 2015, the report claims to be willing to “phase down coal in local electricity generation, optimise the implementation of renewable energy, make our buildings and infrastructure more energy efficient, improve public transport and promote walking as a mobility means, strengthen the climate-readiness of the city as a whole, ‘cool’ the city through landscaping, and partner with stakeholders so that our community can be climate-resilient now and in the long-term”. Specifically, taking as reference the base year 2005, by 2030 it aims at reducing carbon emissions by 26-36%, and carbon intensity by 65-70%. For what concerns the energy efficiency of buildings, the local government has produced the Energy Saving Plan for Hong Kong's built environment (Environment Bureau, 2015) where guidelines to encourage greener buildings are defined, ranging from materials for new buildings to retrofitting the existing ones. As for China, its 13th Five Year Plan on Energy Development, unveiled in January 2017 (Government of China, 2017), establishes particularly high targets, mostly regarding the installation of renewable energy power capacity (210 GW for wind, 110 GW for solar, 380 for hydro), but also limiting the percentage of coal in primary energy consumption below 58% by 2020.

4. Results and discussion

The following Tables (Tables 1, 2, 3, 4) and Figures (Figures 1, 2, 3) show a comparison between the main MuSIASEM End-Use Matrix indicators calculated for both investigated cities, Napoli and Hong Kong. Table 1 and 2 show, at the level of the whole city, the extensive variables Human Activity (HA), Land Use (LU) and Energy consumption in the white columns, while in the grey ones there are the intensive energy indicators: Exosomatic Metabolic Ratio (EMR), that is Energy consumed per hour of human activity, and Exosomatic Metabolic Density (EMD), that is Energy consumed per unit of land (the EMD for liquid fuels is not calculated, because fuel consumption is only related to mobility purposes).

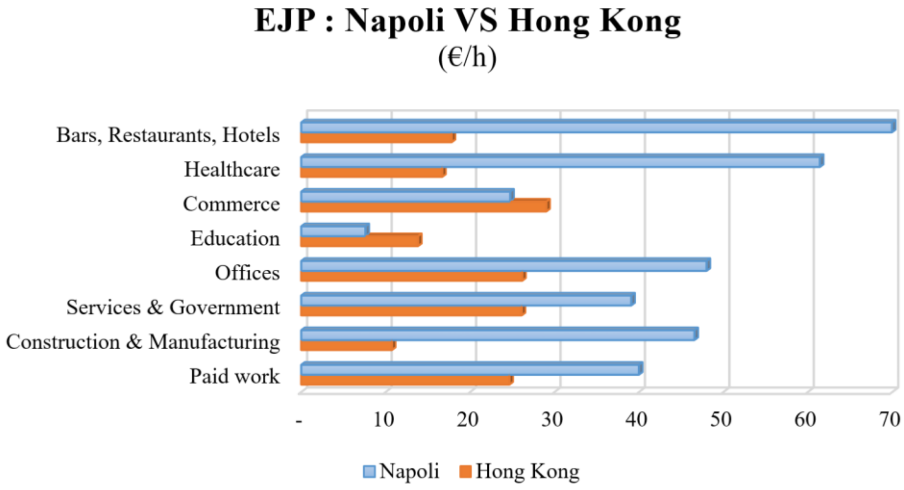

Fig.1. Comparison of Economic Job Productivity (EJP) within the main sectors and for paid work overall.

Table 1. Structuring the system of accounting funds and flows in an end use matrix: variables (Human Activity-HA; Energy; Land Use-LU) and indicators (Exosomatic Metabolic Rate-EMR; Exosomatic Metabolic Density-EMD) at city of Napoli level.

	HA	**EMR Elect.**	**EMR Heat**	**EMR Fuel**	**Energy**			**EMD Electricity/ Land Use**	**EMD Heat/Land use**	**LU**
	Mh	*kWh/h*	*MJ/h*	*MJ/h*	*Elect (GWh)*	*Heat (TJ)*	*Fuel (TJ)*	*GWh/km^2*	*TJ/km^2*	*km^2*
Outside Paid Work										
Residential	6,219.98	0.17	1.40		1,042.95	8,709.87		34.62	289.11	30.13
Mobility	458.06	0.20		33.15	93.13		15,186.39			
Private							12,314.65			
Public					93.13		2,871.74			
Use of S&G	1,408.11									
Paid work	593.26									
C&M	65.66	2.77	35.71		181.91	2,344.86		45.85	590.99	3.97
Agriculture	0.09	52.59			4.73				0	0.09
S&G	523.89	2.73	1.08		1,429.89	567.00				

Notes: The main sources of the data collection were: Eurostudent-Italia (2018); Istat (2018); Tuttitalia (2018); Comune di Napoli (2012); Salvucci et al. (2015). Geographic data on land use were extracted from the Territorial Data Base provided by the Regional Bureau. Data refer to the year 2012, or to the closest year available. (Comune di Napoli, 2012; *Istat*, 2018; *Tuttitalia*, 2018); C&M (Construction & Manufacturing), S&G (Services & Government).

Table 2. Structuring the system of accounting funds and flows in an end use matrix: variables (Human Activity-HA; Energy; Land Use-LU) and indicators (exosomatic metabolic rate-EMR; exosomatic metabolic density-EMD) at city of Hong Kong level.

	HA	**EMR Elect.**	**EMR Heat**	**EMR Fuel**	**Energy**			**EMD Electricity/ Land Use**	**EMD Heat/Land use**	**LU**
	Mh	*kWh/h*	*MJ/h*	*MJ/h*	*Elect (GWh)*	*Heat (TJ)*	*Fuel (TJ)*	*GWh/km^2*	*TJ/km^2*	*km^2*
Outside Paid Work										
Residential	38,412.29	0.30	0.49		11,441.39	18,736.00	8.00	107.58	176.17	106.35
Mobility	3,033.83	0.25	5.07	23.84	756.11	15,384.00	72,317.00			
Private							19,983.00			
Public					756.11		17,213.00			
Use of S&G	15,565.44									
Paid work	7,982.62									
C&M	934.59	2.78	1.19	4.56	2,598.89	1,108.00	4,259.00	204.40	87.14	12.71
S&G	7,016.09	4.03	2.05	0.68	28,281.39	14,388.00	4,769.00			

Notes: The main sources of the data collection were: Census and Statistics Department of Hong Kong; The Hong Kong Factsheets; Thematic Household Survey, Report No. 56 (2015); The Hong Kong Tourism Board (HKTB). Geographic data on land use were extracted from the Census and Statistics Department. Data refer to the year 2012, or to the closest year available. (Department, 2012; *Hong Kong Tourism Board Annual report 2012-2013*, 2013; *Hong Kong Thematic Household Survey, Report No. 56*, 2015). C&M (Construction & Manufacturing), S&G (Services & Government).

Tables 3 and 4 show the same funds, HA and LU, coupled with Economic Value Added (VA). In this case, this generates other two indicators: Economic Job Productivity (EJP), that is the VA created per hour of paid work, and Economic Land Use Productivity (ELUP), that is the VA created per unit of land. Of course, these tables refer only to the Paid Work sector, being this the only one where economic value is created.

Table 3. Variables (Human Activity-HA; Value Added-€VA; Land Use-LU) and indicators (Economic Job Productivity-EJP; Economic Land Use Productivity-ELUP) at Paid Work level, for the city of Napoli.

			Human activity	**EJP**	**€VA**	**ELUP [€/km^2]**	**Land use**
			Mh	*€/h*	*M€*		*km^2*
Paid work PW			**593.26**	**39.99**	**23724.75**		
	Energy Sector		3.62	44.48	160.93		
	C&M		65.66	46.57	3057.69	770.66	3.97
	Agriculture		0.09	293.99	26.42	298.86	0.09
	S&G		523.89	39.09	20479.71		
		Offices	218.27	48.01	10478.93		
		Education	57.18	7.61	434.87		
		Commerce	152.21	24.75	3768.03		
		Healthcare	63.71	61.43	3913.87		
		Bars, Restaurants, Hotels	26.93	69.96	1884.01		

Notes: The main sources of the data collection were: Eurostudent-Italia (2018); Istat (2018); Tuttitalia (2018); Comune di Napoli (2012); Salvucci et al. (2015). Geographic data on land use were extracted from the Territorial Data Base provided by the Regional Bureau. Data refer to the year 2012, or to the closest year available. (Comune di Napoli, 2012; *Istat*, 2018; *Tuttitalia*, 2018). C&M (Construction & Manufacturing), S&G (Services & Government).

Table 4. Variables (Human Activity-HA; Value Added-€VA; Land Use-LU) and indicators (Economic Job Productivity-EJP; Economic Land Use Productivity-ELUP) at Paid Work level, for the city of Hong Kong.

			Human activity	**EJP**	**€VA**	**ELUP [€/km^2]**	**Land use**
			Mh	*€/h*	*M€*		*km^2*
Paid work PW			**7,982.62**	**24.65**	**196,790.88**		
	Energy Sector		31.93	110.94	3,542.24		
	C&M		934.59	10.74	10,036.33	789.34	12.71
	S&G		7,016.09	26.11	183,212.31		
		Offices	4,828.15	26.17	126,358.71	11,428.06	11.06
		Education	159.76	13.83	2,209.47		
		Commerce, other	1,668.59	29,02	48,430.30	3,276.04	14.78
		Healthcare	172.54	16.69	2,880.21		
		Bars, Restaurants, Hotels	187.05	17.82	3,333.62		

Notes: The main sources of the data collection were: Census and Statistics Department of Hong Kong; The Hong Kong Factsheets; Thematic Household Survey, Report No. 56 (2015); The Hong Kong Tourism Board (HKTB). Geographic data on land use were extracted from the Census and Statistics Department. Data refer to the year 2012, or to the closest year available. (Department, 2012; *Hong Kong Tourism Board Annual report 2012-2013*, 2013; *Hong Kong Thematic Household Survey, Report No. 56*, 2015). C&M (Construction & Manufacturing), S&G (Services & Government).

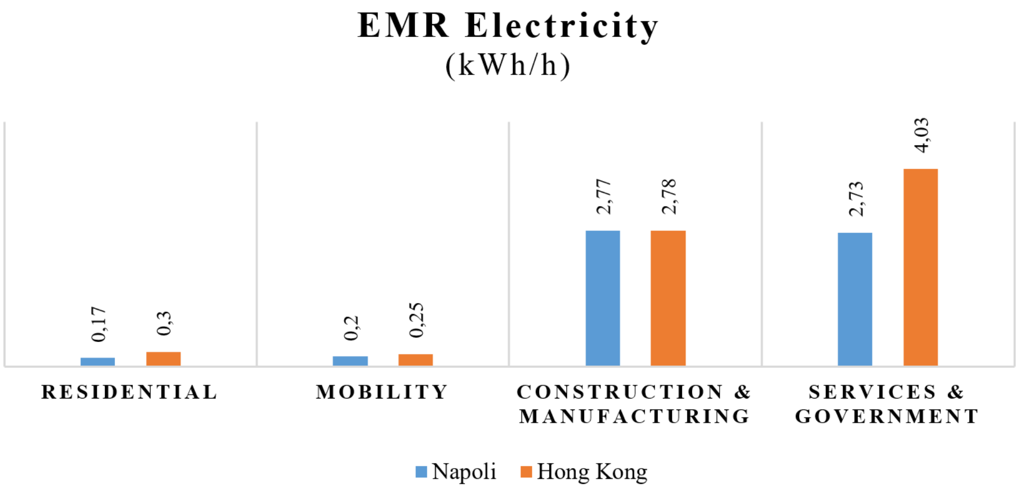

Fig.2. Comparison of Exosomatic Metabolic Ratio (EMR) relative to electricity within four different sectors.

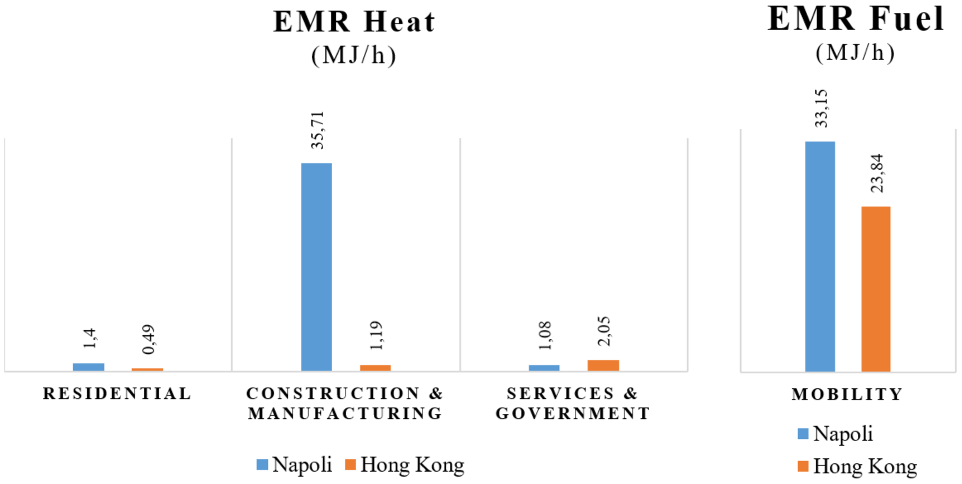

Fig.3. Comparison of Exosomatic Metabolic Ratio (EMR) relative to heat (left) and liquid fuels (right) within different sectors.

The results achieved from the evaluation of the urban metabolism allowed to: (i) identify limits and critical issues, (ii) draw a conclusion and (iii) suggest improvement to be achieved. As it was easy to understand, the economy of both Napoli and Hong Kong is very much shifted to the tertiary sector, which generates 86% and 93% of the added value respectively, and in which 88% (in both cities) of human work is employed.

In Napoli, among services, the subsector with the greatest added value per worked hour seems to be that of catering (restaurants, hotels). This data, however, could be altered by black and informal labor, rather present in the sector .The figures of agriculture, instead, seems to be mostly distorted by inaccurate statistics (see for example (Zucaro, A., Mellino, S., Ghisellini, P., Viglia, 2013). Within the municipal territory, almost completely urbanized, this activity has a pretty marginal size, if not negligible. The presence of so high energy consumption values, and especially those of added economic value, besides the inaccuracy of the statistics may though also represent the great value that is "usurped" by the city from the campaign, especially in the agricultural sector. To arrive at these conclusions, more data would be needed, but part of the anomaly may be due to this factor.

In Hong Kong, agriculture is so marginal that thorough statistics are not even available. Energy sector seems to be quite profitable in the €/h ratio, but its limited percentage within the whole economic system might again have caused misrepresentations. The big disproportion between the two cities in Economic Job Productivity, represented in Paid Work overall and among several subsectors, is due to the fact that Hongkongese people work many more hours per year than Napolitans. In fact, as highlighted in pertinent literature (see, for example, (Petroff, 2015; Yupina, 2018)), Hong Kong has probably the highest "working pace" in the whole world. Contributing to the widening of this gap, on Napoli' side we would probably find other factors, among which: (i) the high rate of unemployment, especially among younger generations, in southern Italy; and (ii) the high standards of European welfare, which allow old people to retire sooner than in other continents.

The results of the Exosomatic Metabolic Ratio (Table 1, Table 2 and Figure 3) highlight, in the case of electricity, values slightly higher for Hong Kong in all sectors. For the residential sector, this might be due to the high density of electrical and digital appliances in Hong Kong's houses, also for uses (e.g. kitchen stove) that in Napoli still rely on natural gas. The same applies to air conditioning and heating in winter time. Hong Kong's climate barely requires any heating system, and in the few cold days people use electric heater, while summer heat requires air conditioning continuously on for several months. On the contrary, Napoli's winter is pretty colder, and nearly every house has water radiators – and this explains the higher Heat EMR -, while only few modern buildings (but the number is increasing) have air conditioning systems.

In the mobility sector, lower Electricity EMR for Napoli might be due to the fact that being public transport very undersized, both in terms of fleet and timetables, it always runs very packed, thus lowering the consumption per person below the level of Hong Kong. Anyways, the comparison with more cities would help to make a more robust guess.

At the same time, higher Fuel EMR clearly translates the more inefficient petrol-fueled transport in Napoli. Main factors of this are probably the obsolescence of southern Italy vehicle fleet, and the stunning traffic jam the city experiences for daily commuting.

Very few cases of MuSIASEM applied to cities exist, and when they do they are often based on different categories (on the need for standardization, see next paragraph), so comparing our results with other studies and verifying their convergence is not an easy task. For example, Lobo et al. (Lobo Aleu and Baeza, 2009) evaluate the energy throughput of Barcelona, but the different forms (electricity, liquid fuels, natural gas) are summed all together. The same happens with Lu et al. (Lu *et al.*, 2016), but in this case we also find en economic assessment of Shanghai, showing an overall EJP of the Paid Work of Shanghai in 2012 (around 9.5 €/h), in line with our results for Hong Kong and Naples (24.6 €/h and 40 €/h, respectively). Convergence of method and results is also found in Sánchez et al. (Sánchez *et al.*, 2017) in which the metabolism of Barcelona city was investigated.

Table 5. Monthly average temperature in Napoli and Hong Kong.

	Monthly average temperature [°C]											
	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Napoli	8.2	8.8	10.6	13.2	17.4	20.9	23.6	23.7	20.8	16.7	12.3	9.3
Hong Kong	15.7	15.4	17.9	21.8	25.4	27.5	28.1	28.4	27.5	24.8	20.9	17.4

5. Conclusions and discussion

MuSIASEM approach, and specifically the End-Use Matrix, proves to be a useful tool for policy makers. Its main strong points seem to be the adaptability to different levels of the picture (wider or narrower), and the ability to keep funds and flows connected. Of course, a greater detail allows more accurate analysis. In these two cases the availability of occupied surface data allocated to the various service sectors would have allowed a comparison between everyone's productivity, as well as their division by area of the city, useful - for example - to allocate funds for building efficiency policies, incentive campaigns to renovate appliances, etc. Likewise, the residential energy consumption divided by district would be an excellent input for this end-use matrix, in such a way as to be able to draw local energy efficiency policies and address them with greater precision.

Of course, the collection of these data by government agencies is clearly a complicated and expensive process, but if integrated with effective analysis tools it can generate great returns and more useful results.

The extreme adaptability of the MuSIASEM, on the other hand, risks to be counterproductive if applied to the scope of policy design. In this case we refer to the need for policy makers to receive standardized analytical tools from science, clear procedures that the community of researchers has already agreed upon. The freedom that the MuSIASEM approach leaves to the analyst can become too abstract and complex for those who must interface with real politics.

In this sense, considering the MuSIASEM a potentially very useful tool, we hope it will be able to reach a standard of procedures and "algorithms" (clearly depending on the areas of application), in order to allow a greater number of standardized analyses, so as to become more replicable and comparable. For instance, the choice of the boundaries of an urban system remains a hot issue to be solved. In order to allow a suitable and reliable comparison among urban systems, the MuSIASEM community could discuss and frame the topic in general guidelines for future studies.

In the direction of integration and systematization of urban metabolism analyses go the efforts of many scientists, for example (Kennedy *et al.*, 2014) which suggests the creation of a single set of urban indicators. In this way, going back to what was already expressed in the introduction, MuSIASEM could contribute substantially to the creation of a suitable pool for the development of a coherent and consistent literature, with a sufficient amount of data to generate abstract and systematic knowledge, and finally arrive to a true science of cities.

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Material, energy and environmental performance of technological and social systems under a Life Cycle Assessment perspective

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ABSTRACT

Selected energy and material resource conversion systems are compared in this paper under an extended LCA point of view. A multi-method multi-scale assessment procedure is applied in order to generate consistent performance indicators based on the same set of input data, to ascertain the existence of constraints or crucial steps characterized by low conversion efficiency and to provide the basis for improvement patterns. Optimizing the performance of a given process requires that many different aspects are taken into account. Some of them, mostly of technical nature, relate to the local scale at which the process occurs. Other technological, economic and environmental aspects are likely to affect the dynamics of the larger space and time scales in which the process is embedded. These spatial and time scale effects require that a careful evaluation of the relation between the process and its surroundings is performed, so that hidden consequences and possible sources of inefficiency and impact are clearly identified. In this paper we analyse and compare selected electricity conversion systems, alternative fuels and biofuels, waste management strategies and finally the time evolution of an urban system, in order to show the importance of a multiple perspective point of view for the proper evaluation of a system's environmental and resource use performance.

1. Introduction

A platform on Life Cycle Assessment (http://lct.jrc.ec.europa.eu/eplca) has been established by the European Commission in support of the implementation of the EU Thematic Strategies on the Prevention and Recycling of Waste and on the Sustainable Use of Natural Resources, the Integrated Product Policy (IPP) Communication and Sustainable Consumption and Production (SCP) Action Plan. The purpose is to improve the credibility, acceptance and practice of Life Cycle Assessment (LCA) in business and public authorities, by providing reference data and recommended methods for LCA studies. The concept itself of LCA stems from the awareness that processes generate impacts in all steps of their lifetime. Upstream impacts relate to a process contribution to deplete the reservoirs of resources (mineral, energy, biotic) while downstream impacts are concerned with emissions and waste generation. LCA techniques are used worldwide to assess material and energy flows to and from a production process. These methodologies are aimed at assessing the environmental impacts of a product (or service) from 'cradle to grave' or better 'from cradle to cradle', including recycling and reclamation of degraded environmental resources. More than a specific methodology, LCA is a cooperative effort performed by many investigators throughout the world (many of which involved in the industrial sectors) to follow the fate of resources from initial extraction and processing of raw materials to final disposal. This effort is day-by-day converging towards standard procedures and common frameworks, in order to make results comparable and reliable. SETAC (the International Society for Environmental Toxicology and Chemistry) developed a "code of practice" to be adopted as a commonly agreed procedure for reliable LCAs (SETAC, 1993). The SETAC standardization has been followed by a robust effort of the International Organization for Standardization (ISO) to

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develop a very detailed investigation procedure for environmental management based on LCT, namely Life Cycle Assessment (International Standards ISO 14040/2006–LCA Principles and framework and 14044/2006 – Requirements and guidelines, www.iso.org). The ISO documents suggest clear and standard procedures for the description of data categories, definitions of goals and scope, statements of functions and functional units, assessments of system boundaries, criteria for inclusions of inputs and outputs, data quality requirements, data collection, calculation procedures, validation of data, allocation of flows and releases, reuse and recycling, reporting of results. Nowhere in the ISO documents is preference given to a particular impact assessment method. In the opinion of the authors, LCA can be looked at as a standardized (and still to be improved) framework, where most of the methodologies already developed for technical and environmental investigations may be included and usefully contribute.

In order to take into proper account the different methodological, spatial and time-scale perspectives, we developed an integrated assessment framework named SUMMA (Sustainability Multi-scale Multi-method Assessment) (Ulgiati et al., 2006). Several case-studies where the SUMMA approach is applied, tested and improved are discussed in this paper.

1.1. Factors of scale and system boundaries

It is self-evident that each evaluation can be carried out at different space and time scales. In general, the local scale only includes direct energy and mass inputs flows (that include a system's assets and infrastructures, discounted over the plant lifetime). As the scale is expanded to the regional level, it includes the production processes for all system 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 of the calculated performance indicators. At this larger scale, raw oil used up in the extraction and refining of minerals and fuel oil itself must also be accounted for. Finally, the large-scale evaluation should also include the ecosystem services that contribute to a process sustainability, such as wind for dilution of emissions, solar radiation and rain water for photosynthesis, the cycling of nutrients and so on. The evaluation may therefore be carried out at three different scales (local, regional and global), each one characterized by well-specified processes (resource final use, manufacturing and transport of components, resource extraction and refining, respectively), so that inefficiencies (poor performance, bottlenecks, generation of undesired co-products, etc.) at each scale may be easily identified and dealt with.

The larger the spatial scale, the larger the cost in terms of material and energy flows, i.e. the worse the related conversion efficiency and other impact indicators. In fact, if a process evaluation is performed at a small scale, its actual performance may not be well understood and may be overestimated due to a lack of inclusion of some large-scale impacts. Depending upon the goal of the investigation, a small-scale analysis may be sufficient to shed light on the process performance for technical or economic optimization purposes, while a large-scale overview is needed to investigate how the process interacts with other upstream and downstream processes as well as the biosphere as a whole. Defining the system boundary and clarifying at what time scale an assessment is performed is therefore of paramount importance, even if the scale of the assessment is sometimes implicit in the context of the investigation. It is very important to be aware that a 'true' value of net energy return or other performance indicators does not exist. Each value of a given indicator is only 'true' at the scale at which it is calculated. When the same value is used at a different scale, it does not necessarily become false. It is, however, out of the right context, and therefore most often useless.

1.2. Accounting for time embodied in resources

Time is an important, although most often neglected, issue in any kind of evaluation. The simplest case is when we have inputs, whose lifetime exceeds the time frame of the analysis. It is easy to transform extended-lifetime inputs into annual flows by dividing by their lifetime (in years). Another and perhaps more important time scale is hidden in the resources used, i.e. the time nature takes to concentrate or produce a given resource (e.g. oil). A resource turnover time is often a good measure of its renewability. An effort to go beyond the concept of turnover time in resource evaluations is the introduction of emergy accounting procedures (Odum, 1988, 1996; Brown and Ulgiati, 2004) that is also included in our extended LCA approach and is discussed later on in this paper.

2. Methods: towards and integrated evaluation approach

Environmental and socio-economic accounting procedures so far proposed by many authors were applied to different space–time windows of interest and were aimed at different investigations and policy goals (Szargut et al., 1988; Odum, 1996; Herendeen, 1998; Ayres and Masini, 1998; Giampietro et al., 1998; Lozano and Valero, 1993; Foran and Crane, 1998; Finnveden and Moberg, 2005; Gasparatos et al., 2008). These authors offered valuable insight towards understanding and describing important aspects of resource conversions and use. However, due to their different focus on specific scales, numeraires and questions, results from these methods are hardly comparable. Further effort is needed towards the development of LCA-like approaches that are capable to integrate different socio-economic and environmental points of view for a more comprehensive picture at different scales. The context and the goal of both the process and the investigation procedure are of paramount importance and likely to affect the results. For example, investigating only the behaviour 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 in such a way as to complement each other, integration would be feasible. Each method may supply a piece of information about system performance at an appropriate scale, to which the others do not apply. Integration supplies an overall picture, characterized by an 'added value' that could not be achieved through each approach individually. The choice of the set of approaches is therefore of crucial importance. Moreover, if the integration is carried out properly, the same set in input data (similar to an LCA inventory, but complemented with other typologies of input, e.g. free environmental flows, environmental services, socio-economic data such as labor and economic services, etc.) may serve to expand the focus of the evaluation beyond the common accounting of energy costs and environmental impacts.

We treated the analysed system or process as a black box, without assigning visibility to any specific details of its internal structure, and firstly carried out a thorough inventory of all the input and output flows 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.

The raw amounts of input and output flows from the inventory phase are multiplied by suitable conversion coefficients specific of

Table 1
Example of table with calculated indicators.

Raw data				
#	Dataset 1 (year, crop, etc.)	Dataset 2	Dataset 3	Dataset 4
Indicator 1	A_1	B_1	C_1	D_1
Indicator 2	A_2	B_2	C_2	D_2
Indicator . . .	$A...$	$B...$	$C...$	$D...$
Indicator $n-1$	A_{n-1}	B_{n-1}	C_{n-1}	D_{n-1}
Indicator n	A_n	B_n	C_{n-1}	D_{n-1}

Table 4
Normalization with reference to the first year of investigation.

Normalized data				
	1985	1993	2002	2006
Indicator 1	A_1/A_1	B_1/A_1	C_1/A_1	D_1/A_1
Indicator 2	A_2/A_2	B_2/A_2	C_2/A_2	D_2/A_2
Indicator . . .	$A_{...}/A_{...}$	$B_{...}/A_{...}$	$C_{...}/A_{...}$	$D_{...}/A_{...}$
Indicator $_{n-1}$	A_{n-1}/A_{n-1}	B_{n-1}/A_{n-1}	C_{n-1}/A_{n-1}	D_{n-1}/A_{n-1}
Indicator n	$A_\mathrm{n}/A_\mathrm{n}$	B_n/A_n	$C_\mathrm{n}/A_\mathrm{n}$	$D_\mathrm{n}/A_\mathrm{n}$

each method applied, which express the "intensity" of the flow, i.e. quantify to what extent a material, energy, or environmental cost is directly or indirectly associated to the flow over its whole life cycle. Such coefficients are available in published Life Cycle Assessment, energy and environmental accounting literature. In so doing, the material, energy, and environmental "costs" associated to each flow are calculated, according to the following generic equation:

$$C = \Sigma C_i = \Sigma f_i \times c_i \quad i = 1, \ldots, n, \tag{1}$$

where C = material, energy or environmental cost associated to the investigated process; C_i = material, energy or environmental cost associated to the ith inflow or outflow of matter or energy; f_i = raw amount of the ith flow of matter or energy; c_i = material, energy or environmental unit cost coefficient of the ith flow (from literature or calculated in this work).

The material, energy or environmental cost C is then divided by the process product, in order to generate its unit cost according to the method applied.

Results are presented in comparative Tables (similar to Table 1) where different impact indicators (energy intensity, global warming potential, etc.) are listed in relation to different datasets (different years or different systems).

Selected indicators are then displayed in radar diagrams. In order to put data with different orders of magnitude together and provide visibility to the performance of the different systems, the following normalization procedures were applied depending on the investigated case:

a) Normalization based on the Standard Score: each individual value calculated is subtracted by the arithmetic mean (μ) and divided by the standard deviation (σ) (Table 2 and Figs. 1 and 3).
b) Normalization with reference to the total impact generated: for each indicator, I_j, the total impact is calculated by adding the values in all datasets (ΣI_j); then, the value of the indicator I_j for a given dataset (year or system) is divided by the total impact ΣI_j in order to calculate its fraction or percentage (Table 3 and Fig. 4).
c) Normalization with reference to the first year of investigation: all values are divided by the value of the first year of investigation (Table 4 and Figs 6 and 8a and b).

Further details of each method used in our integrated assessment are provided as Supplementary material.

3. Results from selected case studies

The case studies presented in this section are the results of specific assessments performed by the authors directly or from literature cases. The joint use of complementary methods, points of view and numeraires allows the generation of a large set of performance indicators that can be used for technological improvement, informed investment choices, comprehensive resource and environmental policy.

The 'upstream' methods are concerned with the inputs, and account for the depletion or appropriate use of environmental resources, while the 'downstream' methods are applied to the outputs, and look at the environmental consequences of the emissions. The calculated impact indicators are interpreted within a comparative framework, in which the results of each method are set up against each other and contribute to providing a comprehensive picture on which conclusions can be drawn. Results reflect the specific characteristics of each case study evaluated and do not claim to be generalisable. They are only presented here to illustrate what can be obtained by means of an integrated approach, not to support or counter the feasibility of a specific technology or process. For this to be done, the number of case studies should be increased, in order to rely on a more representative sample of indicators.

Table 2
Normalization based on the standard score.

Normalized data				
	System 1	System 2	System 3	System 4
Indicator 1	$(A_1-\mu_1)/\sigma_1$	$(B_1-\mu_1)/\sigma_1$	. . .	. . .
Indicator 2	$(A_2-\mu_2)/\sigma_2$	$(B_2-\mu_2)/\sigma_2$	. . .	. . .
Indicator . . .	$(A...-\mu...)/\sigma...$	$(B...-\mu...)/\sigma...$	. . .	. . .
Indicator $n-1$	$(A_{n-1}-\mu_{n-1})/\sigma_{n-1}$	$(B_{n-1}-\mu_{n-1})/\sigma_{n-1}$	. . .	. . .
Indicator n	$(A_n-\mu_n)/\sigma_n$	$(C_n-\mu_n)/\sigma_n$	. . .	. . .

Table 3
Normalization with reference to the total impact generated.

Normalized data				
	System 1	System 2	System 3	System 4
Indicator 1	$A_1/\mathrm{SUM}(A_1+B_1+C_1+D_1)$	$B_1/\mathrm{SUM}(A_1+B_1+C_1+D_1)$	. . .	. . .
Indicator 2	$A_2/\mathrm{SUM}(A_2+B_2+C_2+D_2)$	$B_2/\mathrm{SUM}(A_2+B_2+C_2+D_2)$	. . .	. . .
Indicator . . .	$A_{...}/\mathrm{SUM}(A_{...}+B_{...}+C_{...}+D_{...})$	$B_{...}/\mathrm{SUM}(A_{...}+B_{...}+C_{...}+D_{...})$	. . .	. . .
Indicator $n-1$	$A_{n-1}/\mathrm{SUM}(A_{n-1}+B_{n-1}+C_{n-1}+D_{n-1})$	$B_{n-1}/\mathrm{SUM}(A_{n-1}+B_{n-1}+C_{n-1}+D_{n-1})$	. . .	. . .
Indicator n	$A_n/\mathrm{SUM}(A_n+B_n+C_n+D_n)$	$B_n/\mathrm{SUM}(A_n+B_n+C_n+D_n)$	. . .	. . .

3.1. Cogeneration of heat and electricity

Table 5 compares the results obtained from the application of the integrated approach to a selection of different power plants for electricity and heat generation (from literature or directly investigated by the authors). All the plants were powered by natural gas, but differed by technology (internal combustion engine, gas turbine, steam turbine, combined cycle, fuel cells) and size, ranging from a low power of 0.5 MWe (stand-alone MCFC-Molten Carbonate Fuel Cell plant) up to a high 1200 MWe (NGCC plant). Their technical characteristics and the full details of the evaluations performed are provided in Raugei et al. (2005), Bargigli et al. (2008) and Bargigli et al. (2009). Comparison is made possible by the use of intensive indicators (i.e. indicators per unit of output or indicators of efficiency), that are not dependent on the size of the system.

The calculated performance indicators are comparatively shown in Fig. 1, normalized according to the procedure described in Table 2. According to the overall results summarized by the areas of each diagram, the Natural Gas Combined Cycle, the Hybrid System (MCFC + GT100, a 100 kW gas turbine), and the stand-alone MCFC plants seem to be the ones characterized by the best global performance. It is interesting to note that, while the remaining three plants show performance areas more or less of the same size, the radar diagram allows a clear understanding of the different reasons of the performance achieved. For instance, the STGT plant shows a low electric energy production, that translates into a high energy cost of the kWh generated as well as a low exergy efficiency, in spite of the fact that the exergy efficiency also includes the exergy value of hot water delivered. The STGT plant contributes to the global warming much less than the Gas Turbine or ICE plants per unit of electricity generated: this is due to not only the amount of gas burnt per unit product (that is higher for STGT, as clearly shown in the diagram) but also the indirect emissions for machinery and other factors. It should not be disregarded that the evaluation is carried out over the whole life cycle of the system/product.

Comparing different devices helps choosing among alternatives, based on the set of indicators that are believed more relevant. Instead, when technological or management improvement of an already existing individual plant is the goal, we need to go back to the evaluation procedure, identify the items that contribute more to the bad performance of the system and suggest alternative solutions. As an example, Table 6 provides a summary of the emergy evaluation procedure implemented in the case of the pilot scale MCFC plant (Bargigli et al., 2008). Raw data in the input column are processed according to Eq. (1) by means of conversion factors from emergy literature, to yield the total annual emergy investment (=ecological footprint expressed in emergy units), the transformity (a measure of emergy cost) and other emergy-based performance indicators listed in Table 5. If one of these indicators appears clearly outside of the expected range, Table 6 helps understanding which input flow or which conversion factor is responsible, so that focus can be placed on the search for solutions. Similar tables and related calculation procedures have been constructed for material, energy, exergy and emission assessment of all the power devices in Table 6 as well as the other systems/processes in the next tables and sections. In so doing, both comparison among alternatives and bottleneck identification can be carried out.

Table 5
Performance indicators of selected cogeneration electricity production processes.

Process/product indicator	ICE (Internal Combustion Engine)	MCFC (*) (Molten Carbonate Fuel Cells)	Hybrid (*) (MCFC + GT100)	Gas turbine (TURBEC GT 600)	STGT (steam turbine + gas turbine)	NGCC (Natural Gas Combined Cycle)
Material resource depletion						
MI_{abiot} (g/kWhe)	1030	264	190	640	276	146
MI_{water} (g/kWhe)	3530	1144	870	1890	916	875
MI_{air} (g/kWhe)	=	878	=	=	5003	2655
Energy resource depletion and first law efficiency						
GER of electricity (10^6 J/kWhe)	9.00	10.30	7.83	11.78	13.80	7.35
Oil equiv of electricity (g/kWhe)	215.10	246.00	187.00	281.40	331.00	176.00
Electric energy efficiency	0.40	0.35	0.46	0.20	0.26	0.49
Cogeneration energy efficiency	0.82	0.72	0.72	0.74	0.75	0.71
Exergy, second law efficiency						
Cogeneration exergy efficiency	0.66	0.61	0.62	0.55	0.45	0.60
Emergy, demand for environmental support						
Transformity (10^5 seJ/J), without services	11.10	2.64	4.60	11.10	4.01	1.70
EYR	1.02	=	1.00	1.01	=	=
ELR	63	=	1896	73	=	=
Climate change						
GWP (CO_2-equiv, g/kWhe)	921	583	493	788	750	398
Acidification (SO_2-equiv, g/kWhe)	=	0.33	=	=	0.62	0.54

Source of data: Raugei et al. (2005), Bargigli et al. (2008, 2009).

(*) Data for MCFC systems are from pilot scale production. As such, the corresponding results presented here should not be considered to be fully representative of the current or future state of the art.

3.2. Alternative fuels and biofuels

Fuels and biofuels alternative to the commonly used fossil gasoline and diesel were explored and results presented in Table 7 (absolute values). A more detailed discussion of each process investigated (syngas, hydrogen, biofuels) as well as of the meaning of the results obtained is provided in Bargigli et al. (2004) and Giampietro and Ulgiati (2005).

Table 6
Emergy evaluation of a hybrid system (MCFC + GT100) integrated with auxiliary boilers (Bargigli et al., 2008).

Item	Raw amount (kg/yr)	Unit	Specific emergy (*) (seJ/unit)	Emergy of item (seJ/yr)
MCFC compact unit				
Cell modules (4 × 125 kW)				
Matrix (a-LiAlO$_2$)	4.18E+05	g/yr	2.92E+11	1.22E+17
Ni cathode	1.46E+05	g/yr	4.33E+11	6.32E+16
carbonated anode (Ni/Cr)	3.94E+05	g/yr	3.55E+11	1.40E+17
Electrolyte Li$_2$CO$_3$/Na$_2$CO$_3$	1.50E+05	g/yr	2.57E+11	3.86E+16
Special steel parts in modules (AISI 310)	8.97E+06	g/yr	6.20E+09	5.56E+16
Natural gas for start-up	7.62E+05	g/yr	4.56E+09	3.47E+15
Deionised water for start-up	2.65E+06	g/yr	3.44E+06	9.12E+12
Natural gas for operation	1.34E+09	g/yr	4.56E+09	6.11E+18
Deionised water for steam	4.68E+09	g/yr	3.44E+06	1.61E+16
Microturbine GT100 (including materials for maintenance)				
Steel (17% Cr, 12% Ni)	5.71E+04	g/yr	7.22E+09	4.12E+14
Plastic	3.54E+05	g/yr	1.30E+10	4.60E+15
Filter material	4.77E+04	g/yr	1.57E+10	7.49E+14
Rubber	2.96E+04	g/yr	2.19E+10	6.48E+14
Lube oil	3.88E+03	g/yr	9.92E+09	3.85E+13
Deionised water	4.12E+03	g/yr	3.44E+06	1.42E+10
Battery (as a whole)	6.53E+03	g/yr	3.09E+10	2.02E+14
Complementary boilers				
Natural gas	1.37E+09	g/yr	4.56E+09	6.25E+18
Steel (17% Cr, 12% Ni)	2.00E+04	g/yr	7.22E+09	1.44E+14
Total emergy invested		seJ/yr		1.28E+19
Total electricity generated	2.78E+13	J/yr		
Transformity of electricity generated		seJ/J	4.60E+05	

(*) Values of specific emergies for MCFC and microturbine GT100 components are from Ulgiati et al. (2002, 2005) as well as Bargigli (2003); values for steel are from Bargigli and Ulgiati (2003); all other values from main emergy literature (Odum, 1996; Odum, 2000; Brown and Ulgiati, 2004). All values updated to the new biosphere emergy baseline (Odum, 2000), when needed.

Fig. 2 shows the system diagram of the industrial conversion of corn into ethanol. The main process steps are indicated and the evaluation was performed step by step, in order to be able to identify the parts of the process that are crucial for the final performance. The diagram indicates the main input flows (matter, energy and labor) that support each step of the process; these flows are then listed in an inventory table and converted into embodied matter, embodied energy, exergy, emergy and emission flows according to the approach described in Section 2. System diagrams are an important tool for integrated assessment since, unlike other kinds of commonly used flow diagrams, they provide a pictorial description of the whole process, its driving forces (material and energy flows, free environmental flows, other non-material flows), products, recycling patterns, as well as interactions among components, which are all important aspects of an integrated assessment.

The final results for the investigated fuels are compared in the radar diagram of Fig. 3, normalized according to the procedure described in Table 2. As with the previous radar diagrams, values are adjusted for better visualization and a larger area indicates a worse performance. i.e. identifies the system that is characterized by the largest potential impact. Among the fuels in Fig. 3, hydrogen from water electrolysis is the option that shows the worst performance in most impact categories. The other fuel options show more or less the same impact area, although they are characterized by specific aspects of weakness that should be addressed for improvements. Bioethanol and biodiesel are penalized by a large water demand as well as by a relatively high value of their transformities. The value of these two indicators are not a good sign of performance, because water places a huge constraint on biofuel feasibility and transformities higher than the transformity of fossil fuels indicate the lack of real renewability of such typologies of fuel. Considering the very large value of the abiotic material intensity of syngas from coal (namely, too much matter is excavated, transported and processed per unit of energy delivered) we remain with hydrogen from steam reforming of natural gas as the most viable option to provide a transportation fuel, among those investigated (conventional gasoline and diesel are not included in the assessment). In any

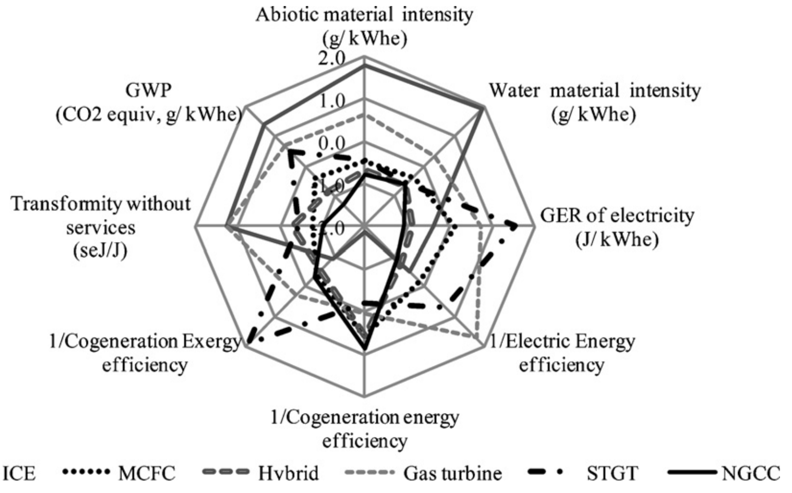

Fig. 1. Radar Diagram with performance indicators of selected cogeneration electricity production processes.

Table 7
Performance indicators of selected fuels and biofuels.

Process/ product indicator	Syngas (from coal gasification)	Hydrogen (from steam reforming of natural gas)	Hydrogen from water electrolysis (thermoelectricity)	Bioethanol (from corn)	Biodiesel (from sunflower)	Methanol (from wood)
Material resource depletion						
MI_{abiot} (g/g)	30.90	3.60	12.20	7.45	13.97	=
MI_{water} (g/g)	40.80	10.60	71.80	4811	2853	=
MI_{air} (g/g)	8.80	21.30	165.10	=	=	=
MI_{biot} (g/g)	=	=	=	0.35	0.79	=
Energy resource depletion and first law efficiency						
GER (10^4 J/g)	2.20	18.80	42.90	2.51	3.43	0.47
Oil equiv (g_{oil}/g)	0.48	4.48	10.20	0.60	0.82	0.11
Energy Return on Investment (EROI)	0.76	0.64	0.28	1.15	0.98	1.10
Exergy, second law efficiency						
Exergy efficiency	0.75	0.71	0.27	=	=	=
Emergy, demand for environmental support						
Transformity without L&S (10^4 seJ/J)	9.56	12.30	36.60	18.90	23.10	26.60
EYR	=	=	=	1.24	1.09	2.35
ELR	=	=	=	10.90	25.90	2.10
Climate change						
Global warming (CO_2-equiv, g/g)	5.20	9.50	33.70	2.02	3.21	1.54
Solid emissions (g/unit)	3.00	=	=	=	=	=

Source of data: Bargigli et al. (2004) and Giampietro and Ulgiati (2005).

case, a compromise between different performance parameters is always needed when making a choice.

3.3. *Waste management*

Four different urban waste management processes related to the city of Rome, Italy, were investigated by Cherubini et al. (2008, 2009). The study focused on (1) landfilling, (2) landfilling with biogas recovery, (3) conversion to biogas and Refuse Derived Fuel (RDF, for electricity production), and finally (4) direct incineration and electricity production. Calculated indicators are shown in Table 8. All steps were accounted for, including preliminary sorting of recoverable materials, collection and transport, landfilling of combustion ash and biogas digestion process. The energy generated from waste biomass was credited to the process, in so decreasing the global energy cost of management and the global emissions from the whole cycle. Performance indicators relative to the energy delivered (mainly electricity) are also shown in Table 8. In one case (conversion to biogas and RDF) the process delivers a non-negligible amount of net energy, so that the net emissions (=actual process emissions minus avoided emissions due to the energy delivered) are negative.

The radar diagram of Fig. 4, normalized according to the procedure described in Table 3, allows a relative comparison of the three processes characterized by energy recovery (landfilling without energy recovery is not shown), suggesting that waste sorting and conversion to biogas and RDF (Refuse Derived Fuel) is the best alternative (=the one with smaller impact area, within the selected set of relevant indicators). Landfilling with biogas recovery and direct incineration, i.e. the most commonly used technologies, are also the ones characterized by the higher global impact, mainly on the downstream side.

3.4. *Urban systems*

The metabolic patterns of an urban system (Rome, Italy) were investigated from 1962 to 2002 by Ascione et al. (2008, 2009). Fig. 5 shows a system diagram of the city and its surrounding environment (natural areas, agriculture) and infrastructure. The investigation took into account all the matter, energy, and emergy flows supporting the urban system over 40 years of growth and development, with the aim of ascertaining the total cost of sup-

Table 8
Performance indicators of urban waste management, Roma, Italy.

Process/product Indicator	Landfilling	Landfilling with biogas recovery (*)	Sorting and conversion to biogas and RDF (*)	Direct incineration (*)
Material resource depletion				
MI_{abiot} (g/ g_{waste})	0.24	0.24	0.30	0.36
MI_{abiot} (g/ kWhe)	=	1899	334	552
MI_{water} (g/unit)	0.03	0.02	2.09	1.04
MI_{abiot} (g/ kWhe)	=	0.82	2398	1578
Energy resource depletion and first law efficiency				
GER (kJ/g_{waste})	0.05	2.15	9.71	9.52
GER (J/kWhe)	=	2.67E+07	1.38E+07	1.60E+07
$GER_{oil\ equiv}$ (g_{oil}/g_{waste})	0.001	0.05	0.23	0.23
$GER_{oil\ equiv}$ (g_{oil}/kWhe)	=	637.84	329.67	382.23
Energy efficiency	=	13%	52%	22%
Emergy, demand for environmental support				
Specific emergy (10^8 seJ/g_{waste})	1.58	1.54	1.22	1.83
Transformity with L&S (seJ/kWhe)	=	5.36E+05	2.28E+04	8.66E+04
Climate change				
Global warming (CO_2-equiv, g/g_{waste})	1.31	0.59	−0.23	0.15
Acidification, total emissions (SO_2-equiv, mg/ g_{waste})	0.37	0.13	−0.30	0.53

Source of data: Cherubini et al. (2008, 2009).
(*) Followed by conversion to electricity.

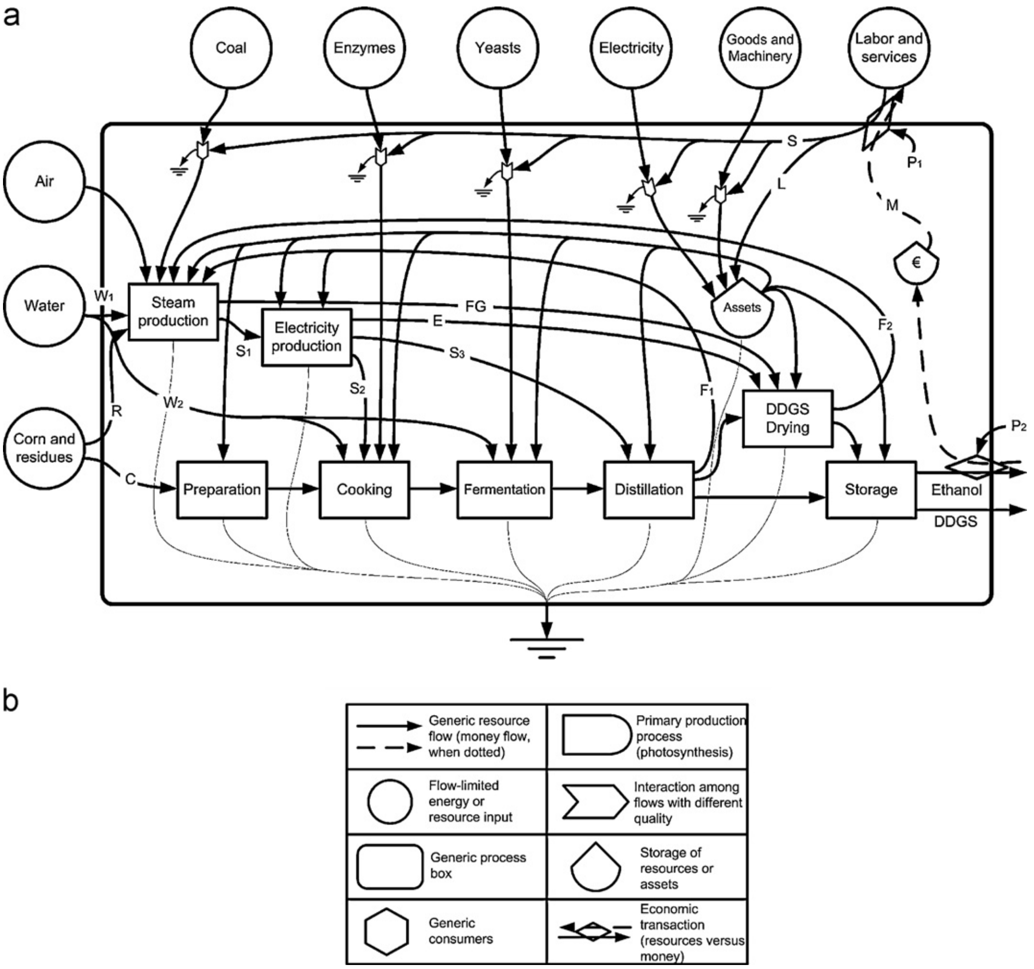

Fig. 2. (a) Systems diagram of the industrial conversion of corn into bioethanol. (b) Explanation of systems symbols (Odum, 1996). Meaning of abbreviations in (a): C: corn fed to the ethanol plant; R: agricultural residues fed to the boiler for process heat; W_1: process water for steam production; W_2, W_3: cooling water supplied to the cooking and fermentation steps; S_1: high pressure steam for electricity production; S_2, S_3: low pressure steam supplied to the cooking and fermentation steps; E: electricity produced within plant and used for DDGS drying; FG: flue gases co-produced with steam and used for DDGS drying; F_1: low pressure water condensate fed-back to the Steam Production steps; F_2: warm gases fed-back to the Steam Production step; L: labor flux into the process; S: services, i.e. labor previously performed for the production and supply of resources and goods used in the process; M: monetary flux against the product flow. Money from sale of product(s) is used to purchase labor and services. P_1: purchase price of labor and services; P_2: sale price of ethanol and DDGS; DDGS: Distillery Dried Grains with Solubles.

porting the urban system, its population, its economic activity and generation of GDP.

More than 20 indicators of performance and sustainability were calculated in this urban case study and their trends compared and discussed. The above waste management case study (Section 3.3) was part of such an investigation effort, with focus on a specific sector (waste) that plays an important role in the whole urban metabolism. Results, shown in Table 9, point out a continuous growth of resource demand by the urban system. Unfortunately, such a demand was mainly demand for non-renewable flows from outside the system, thus making it largely dependent on imports. Simply focusing on one individual parameter, it is very interesting to note that in the year 2002 the energy use per person in Rome was about 6.5 t oil equivalent. The calculation procedure carried out according to Eq. (1) allowed to point out that transportation fuels accounted for about 2.0 t oil equivalent per person, electricity and water about 0.7 t, space heating about 0.5 t and food production only for a low 0.1 t. The remaining energy use (about 3 t per person was mainly due to construction material, infrastructures and other imported goods. In the same year, a citizen of Rome used virtually 4.5 ha of land (directly and indirectly used for goods and energy supply), against the 0.05 ha per person actually available. A policy maker concerned for wise resource use and environmental problems can certainly find in these data a good starting point.

The radar diagram in Fig. 6 was drawn by normalizing each performance index relative to the value of the same index in the year 1962, according to the procedure suggested in Table 4. The figure shows very clearly the impressive expansion of the urban system's impact over time, due to both increase of population and increase in demand for resources. The expansion seems to have been accelerating in the last decades. It is important to note that the main driver for such an increased impact is the increased energy use (total and per capita), that also translates into increased combustion and release of chemical species contributing to global warming and rain acidification.

3.5. Agriculture

A case study about the agricultural sector of Campania region in Southern Italy was performed and its performance assessed over a time span of 20 years (Ulgiati et al., 2008). As with the previous case studies, an inventory of the main input and output flows served as a basis for assessing the direct and cumulative support by

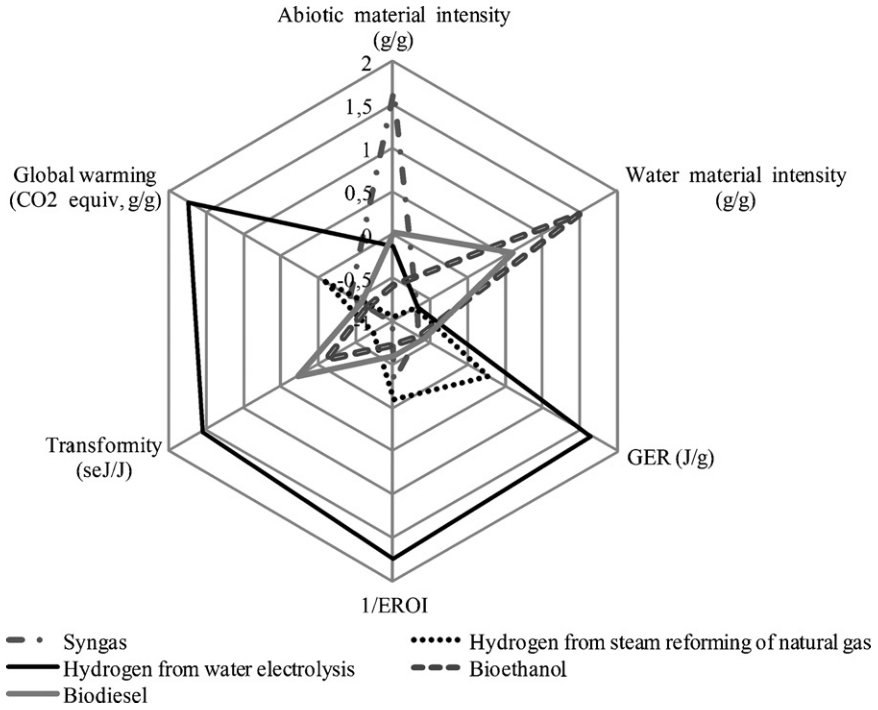

Fig. 3. Radar diagram with performance indicators of selected alternative fuel production processes. Methanol is not included in the graph due to the fact that some indicators were not available in the case study referred to in Table 7.

the economic system as well as by the environment. The systems diagram of the process is shown in Fig. 7, where all input flows from the environment and the economy are indicated together with system's components and internal exchanges of matter and energy.

The calculated performance indicators are listed in Table 10 and graphically shown in the radar diagrams of Fig. 8a (upstream performance indicators) and Fig. 8b (downstream performance indicators), where the normalization procedure described in Table 4 was used.

Fig. 8a shows an increased demand for energy, matter and environmental support per unit product, all translating into an increased Environmental Loading Ratio ELR in the years 2002 and 2006, compared to the previous years investigated. Such a trend is due, depending on the years, to changed mix of crops, changed machinery use, changed climate conditions (mainly less rainfall), changed market value of products, changed amount of land cropped. In particular, it should be highlighted that the year 1993 was characterized by an agricultural production larger than the other years, which translated into a much smaller impact area per unit product even with respect to the year 1985 chosen as a reference. The agricultural land cropped in the year 1993 was also larger, so that the global contribution to downstream LCA impact categories (Fig. 8b) was the largest among the years investigated.

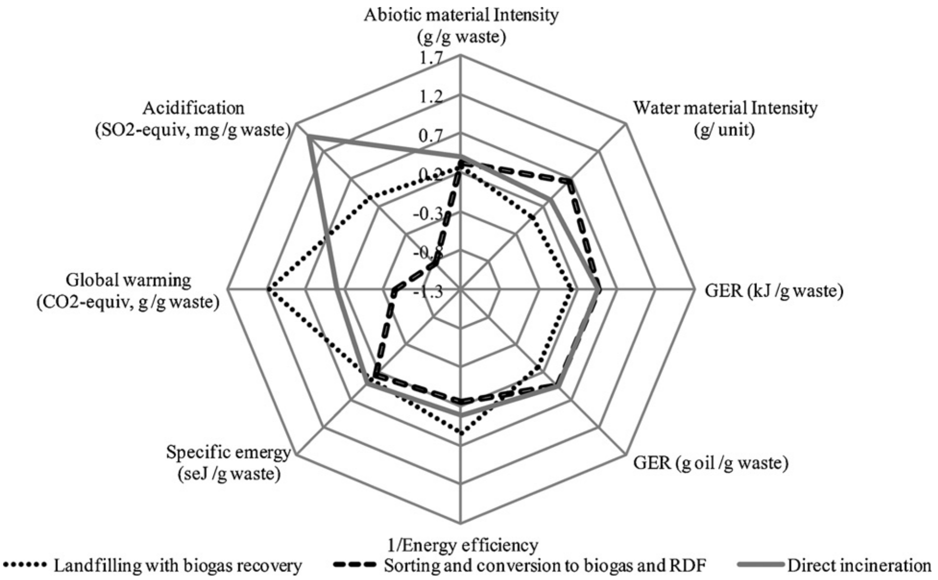

Fig. 4. Radar diagram with performance indicators of selected waste management processes with energy recovery.

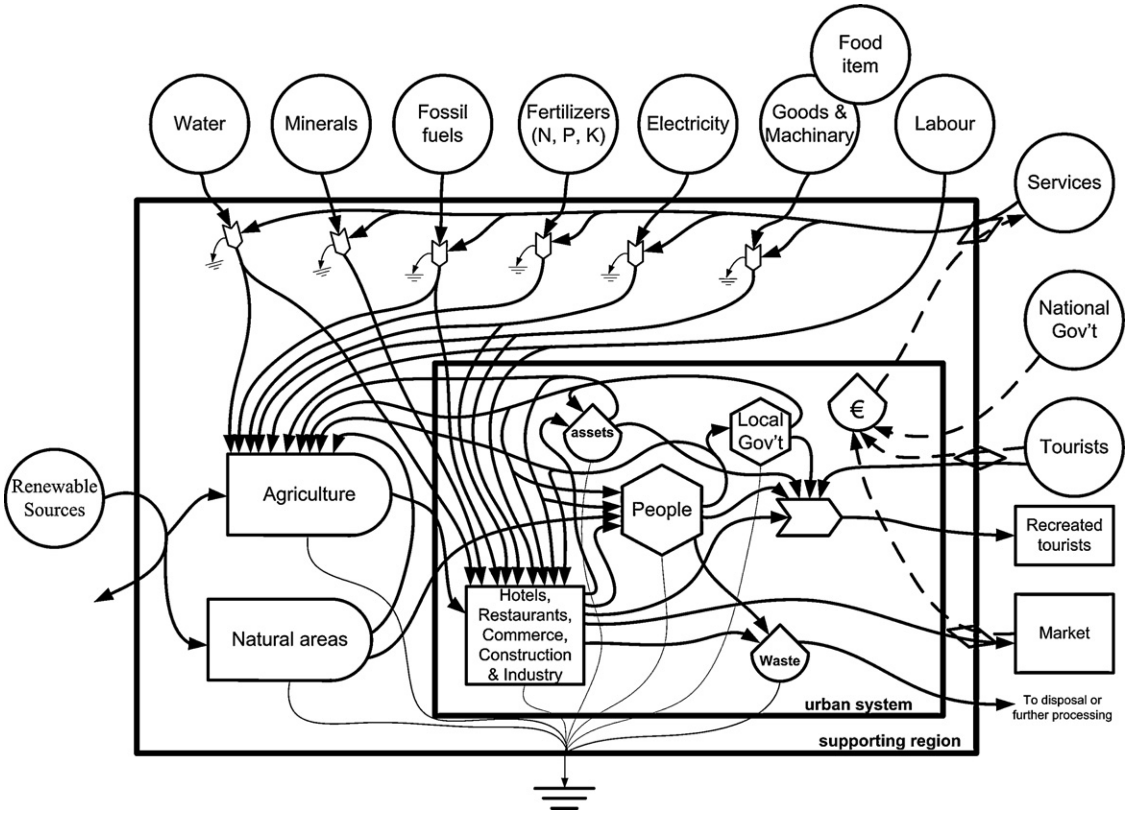

Fig. 5. Systems diagram of an urban system within its surrounding region (systems symbols from Fig. 2b).

Instead in Fig. 8c, that shows the same impact categories quantified per unit of product (grams, dry matter), the situation is reversed, with better performances in the years 1985 and 1993 and a sharp drop in the years 2002 and 2006. Comparison between Fig. 8b and c clearly points out – once again – the importance of, and the need for, performing an assessment under different points of view and by means of both extensive and intensive indicators. In fact, while the extensive indicators depend upon the size of cropped area (in so providing a measure of the global impact generated), the intensive indicators provide a joint assessment of cost (inputs) and benefits (products) translating into different kind of efficiencies (investment of matter, energy, water, environmental support, per unit product, per unit economic value generated, per ha of land cropped as well as per unit labor applied).

Table 9
Trend of urban metabolism, Roma, Italy (1962–2002).

Year indicator	1962	1972	1982	1992	2002
Material resource depletion					
MI_{abiot} (10^7 g/person)	1.72	2.93	2.82	3.87	4.50
MI_{abiot} (10^3 g/€)	82.70	40.60	5.98	2.30	1.99
MI_{water} (10^8g/person)	3.19	4.91	5.65	6.82	8.16
MI_{water} (10^4 g/€)	154	68.20	12.00	4.05	3.61
Energy resource depletion and energy efficiency					
GER per person (10^{10} J/person)	6.34	11.40	14.80	19.70	27.30
GER per unit currency (10^7 J/€)	30.50	15.80	3.14	1.17	1.21
Oil equiv (10^6 g/person)	1.52	2.72	3.54	4.72	6.51
Oil equiv (10^2g/€)	73.00	37.80	7.51	2.80	2.88
Emergy, demand for environmental support					
Specific emergy with L&S (10^{16} seJ/person)	2.61	3.53	3.92	6.36	5.45
Specific emergy with L&S (10^{12} seJ/€)	126	49.10	8.33	3.78	2.41
EYR	1.05	1.03	1.02	1.01	1.02
ELR	40.85	61.94	52.38	94.73	64.47
Ecological footprint					
Area per person (ha/person)	2.30	2.44	3.22	3.36	4.51
Area per unit GDP (ha/€)	0.0111	0.0035	0.0007	0.0002	0.0003
Climate change					
Global warming (10^6 CO_2-equiv, g/person)	4.62	8.42	11.00	14.40	20.00
Global warming (10^2 CO_2-equiv, g/€)	223	117	23.40	8.57	8.83
Acidification (10^4 SO_2-equiv, g/person)	1.30	2.54	3.08	4.00	5.67
Acidification (SO_2-equiv, g/€)	62.70	35.30	6.54	2.38	2.51

Source of data: Ascione et al. (2008, 2009).

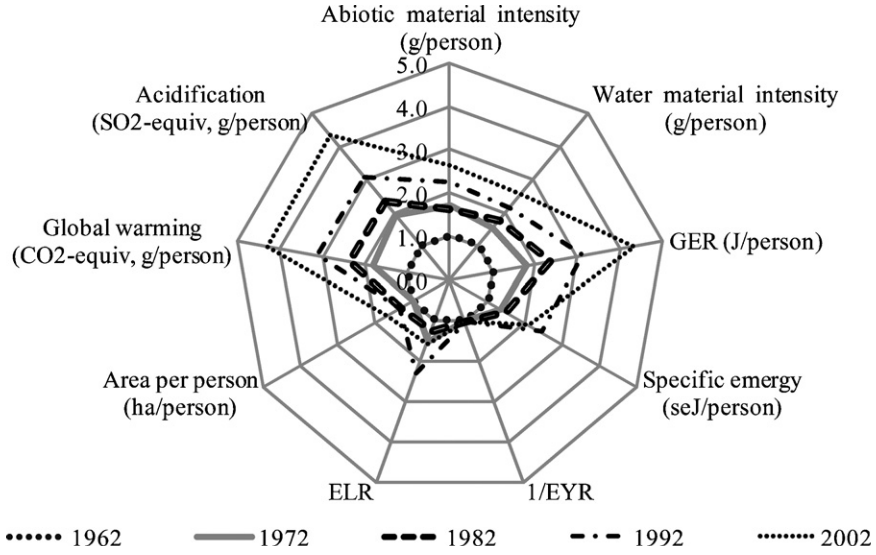

Fig. 6. Radar diagram with performance indicators of urban metabolism over time, Rome, Italy (1962–2002).

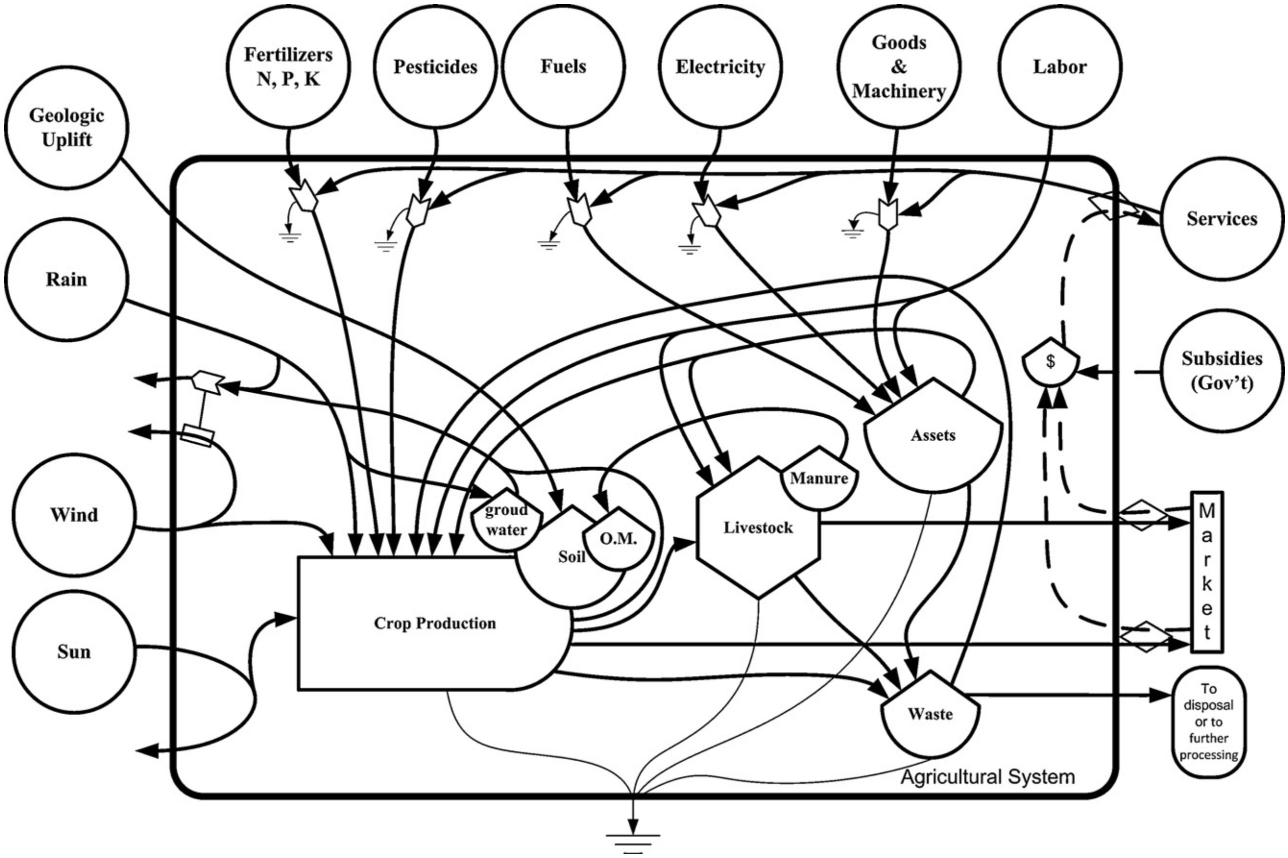

Fig. 7. Systems diagram of a regional agricultural system (systems symbols from Fig. 2b).

Table 11 summarizes the energy inflows in support of the regional agricultural system (Ulgiati et al., 2008). As with Table 6 (emergy evaluation of electricity production) the energy calculation procedure is carried out according to Eq. (1): raw inputs of energy and matter are multiplied by embodied energy intensities from literature to yield the total energy annually used by the system directly or indirectly and a large set of indicators (among which those listed in Table 10 for selected years). Fuels for agricultural machinery (also including the fuel indirectly used for fuel transport and refining), electricity for irrigation and nitrogen fertilizers clearly appear as the most important energy inputs to the agricultural sector.

4. Discussion

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 sur-

Table 10
Trend of the agricultural sector of Campania region, Italy (1985–2006).

Indicator year	1985	1993	2002	2006
Material resource depletion				
MI_{abiot} ($g/g_{d.m.}$)	0.30	0.24	0.60	0.57
MI_{abiot} (10^3 g/€)	2.31	1.84	1.28	1.30
MI_{water} (10 g/g $_{d.m.}$)	3.84	1.89	3.23	2.37
MI_{water} (10^5 g/€)	2.98	1.43	0.69	0.54
Energy resource depletion and energy efficiency				
GER per unit mass (10^3 J/ $g_{d.m.}$)	1.24	1.32	2.80	2.97
GER per unit currency (10^6 J/ €)	9.65	9.97	6.00	6.82
Oil equiv ($g/g_{d.m.}$)	0.03	0.03	0.07	0.07
Oil equiv (10^2 g/ €)	2.30	2.38	1.43	1.63
EROI ($10^{1)}$	1.34	1.26	0.58	0.53
Emergy, demand for environmental support				
Specific emergy with L&S (10^8 seJ/ $g_{d.m.}$)	4.16	4.30	10.11	11.49
Specific emergy with L&S (10^{12} seJ/€)	3.24	3.25	2.17	2.63
EYR (with L&S)	1.30	1.19	1.16	1.14
ELR (with L&S)	3.71	5.81	6.81	7.75
Climate change				
Global warming (CO_2-equiv, $g/g_{d.m.}$)	0.10	0.10	0.20	0.21
Global warming (10^2 CO_2-equiv, g/€)	7.54	7.61	4.35	4.91
Acidification (10^{-2} SO_2-equiv, $g/g_{d.m.}$)	0.03	0.03	0.06	0.06
Acidification (SO_2-equiv, g/€)	2.36	2.50	1.34	1.43

Source of data: Ulgiati et al. (2008).

rounding environment. Processing these data in order to calculate performance indicators as well as material and energetic intensities makes it possible to compare the process output to other products of competing processes. Results may differ depending on the goal, the boundaries, the time scale, and the technology and may suggest different optimization procedures. If the analyst is able to provide comprehensive results as well as to explain divergences at the appropriate scales of the investigation, a process can be more easily understood. Conclusions are also reinforced and are more likely to be acceptable for research, application and policy strategies.

4.1. The 'added value'

Assessing a process performance on different scales offers an effective way to refine the analysis and improve the process. Results from the simultaneous application of a multiple set of methods yield consistent and comparable performance indicators and call for a two-fold optimization pattern:

a) Upstream: trying to decrease the use of or replace those input flows which affect the material, energy and environmental support demands more heavily;
b) Downstream: trying to decrease the use or avoid misuse of the investigated product, in order to negatively affect the input demand by controlling the end of the life cycle chain.

As already pointed out in the introduction, it was the authors' explicit choice not to provide a means of combining the results from the different upstream and downstream methods into one single "super-indicator", since this is contrary to the fundamental idea that separate indicators provide a much more comprehensive environmental profile, the interpretation of which should be left to the analyst. The latter should in fact clarify to the maximum possible extent the meaning and all the possible implications of the single results, highlighting the often inevitable trade-offs that all strategic choices entail, rather than simply attach to them one numerical tag, which would inevitably conceal much of the valuable detail of the study.

Last but not least, since the approach is based on a single common inventory of all the system's inputs and outputs, a systematic sensitivity analysis can simultaneously be 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 in the spreadsheet-based calculation procedures. Such an analysis is invaluable in order to estimate the actual reliability of the impact

Table 11
Embodied energy evaluation of the agricultural sector of Campania region (Italy) in the year 2006 (Ulgiati et al., 2008).

Flow	Unit	Raw amount	Oil equivalent (g/yr)	Embodied energy (J/yr)
Gasoline	g/yr	3.32E+10	3.71E+10	1.55E+15
Additional energy (heavy fuel oil) for gasoline refining	g/yr	5.34E+09	5.44E+09	2.28E+14
Diesel and heavy fuel	g/yr	1.13E+11	1.24E+11	5.19E+15
Additional energy (heavy fuel oil) for diesel refining	g/yr	2.36E+10	2.40E+10	1.00E+15
Electricity	J/yr	8.87E+14	5.30E+10	2.22E+15
Water for irrigation	g/yr	1.04E+14	1.37E+10	5.72E+14
Nitrogen (N) fertilizer	g/yr	4.25E+10	7.44E+10	3.12E+15
Phosphate (PO_4) fertilizer	g/yr	2.01E+10	6.43E+09	2.69E+14
Potassium (K_2O) fertilizer	g/yr	1.03E+10	2.26E+09	9.48E+13
Fungicides	g/yr	3.23E+09	4.33E+09	1.81E+14
Insecticides	g/yr	1.00E+09	1.27E+09	5.32E+13
Acaricides	g/yr	8.00E+08	1.74E+09	7.28E+13
Agricultural machinery				
Steel and iron	g/yr	7.22E+09	6.57E+09	2.75E+14
Aluminium	g/yr	1.23E+09	6.61E+09	2.77E+14
Rubber and plastic material	g/yr	8.81E+07	2.64E+08	1.11E+13
Fraction of copper	g/yr	2.64E+08	5.84E+08	2.44E+13
Total direct and indirect energy cost			3.62E+11	1.51E+16

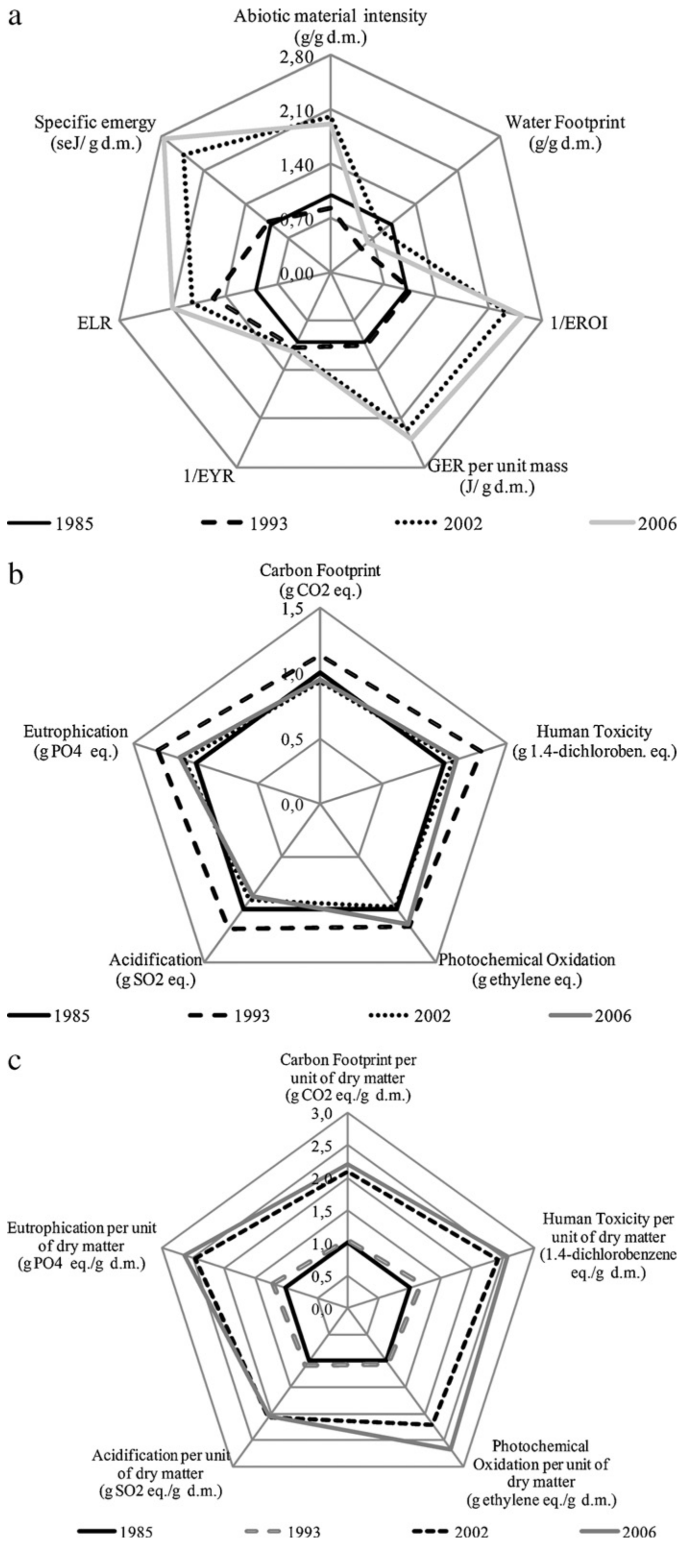

Fig. 8. Radar diagrams with performance indicators of the agricultural system of Campania region (Italy) over time (1985–2006): (a) selected upstream performance indicators; (b) selected downstream environmental performance indicators (extensive indicators, whole regional agriculture); (c) selected downstream environmental performance indicators (intensive indicators per unit of product).

assessment itself, accounting for the inevitable uncertainties and variability in the input data and/or impact coefficients, as well as to single out which are the most critical key points of the analysed process in the light of the different assessment methods.

4.2. Weighting factors

Tables 5–12 list a selection of the calculated performance indicators and related calculation schemes. In general, many more indicators are generated by an integrated approach, but listing all of them is not necessary for the purpose of the present paper. If the focus is on the specific behaviour of the system from a single point of view (e.g. energy consumption), the analyst can refer to the calculation procedure that leads to that specific indicator and look carefully at the options available to minimize such an impact. Each choice can be tested in the calculation procedure (either implemented within an excel platform or a commercial software) and its consequences can be simulated, being aware that the improvement of the value of one indicator may lead to the worsening of another one. Since inventory data are linked to all the calculation procedure of all the indicators, this is a relatively easy task.

If the goal is providing a global picture of a process impact, then a selection of many indicators is needed in order to have a comprehensive evaluation across space and time scales. Since many indicators are generated by the same calculation procedure (e.g. Gross Energy Requirement, energy efficiency, EROI; or EYR, ELR, transformity) the analyst might select them according to his/her experience or according to the specific target of the investigation (e.g. assessing the environmental sustainability of the process). Once indicators are chosen, they can be normalized and diagrammed in such a way (histograms, radar, lines) that their values can be compared to a reference value or year, or simply looked at together, in order to provide a global picture of the impact. This is the case, for example, of Figs. 1, 3 and 4, where several systems are compared with each other and the normalization is performed in such a way that the area within each curve indicates a measure of the impact relative to the other processes investigated for comparison. Instead, Figs. 6 and 8 show the behaviour of an urban system and an agricultural sector over time, by referring to the global performance in a given year. In this case, the larger the area the larger the variation of the impact over time, i.e. the diagram assesses how fast is the change for each individual impact and globally.

All the radar diagrams put a selection of indicators on each axis. Such a choice might lead to the erroneous assumption that their impacts are the same. Each indicator refers to a specific impact category in LCA as well as other evaluation methods (e.g. contribution to global warming, demand for environmental support, water footprint) and certainly refers to a different impact on the global environment. Assigning weighting factors to the whole assessment is not easy nor there is any agreement in the scientific community in this regard, so that such a step is not recommended in the ISO norms (ISO 14040/2006; ISO 14044/2006) that codify the LCA approach. In fact, weighting and grouping is explicitly discouraged by ISO 14044/2006 for all studies intended for public disclosure. Our choice of diagramming all the indicators as if they were at the same level does not affect the final understanding of the impact, because assigning a different weighting factor to all indicators in Figs. 1, 3 and 4 would change their values for all the investigated processes, but would leave the ranking unchanged. Same would happen with Figs. 6 and 8. The shapes and areas in the diagram would be affected by choosing weighting factors, but relative ranking would not and therefore the same relative impacts would be suggested by the diagram. Some evaluation methods suggest weighting factors and end-point scores (Eco-Indicator 1999), but the debate about the opportunity of such a choice is still open. However, we do not compare data and indicators pertaining to different impact categories, but always compare the value for one category with the corresponding value in other years or for another device; as a consequence, no weighting factors need to be applied.

4.3. Optimization procedures

The ultimate goal of any investigation about a process is to generate a clear picture of the crucial steps as well as crucial input and output flows, i.e. those steps and those flows that affect more heavily the process performance. In so doing it is possible to focus on these steps and flows, to understand how important are they in the global economy of the investigate process, and to suggest changes capable to lead to an improved performance. Some steps may be replaced by alternative patterns, some flows may be decreased by means of more efficient machinery or sub-processes, and finally some flows may simply be avoided without any important consequence for the final product. Suggesting an optimization procedure is not an easy task. Indicators are the result of a calculation procedure where the inventory data are multiplied by intensity factors specific of each given method (e.g. oil equivalent factors, transformity, global warming potential, etc.). Therefore, when a performance indicator (e.g. the Acidification Potential for a coal powered plant) is not satisfactory, the analyst goes back to the calculation procedure in order to identify the input items that are responsible of the largest contributions to that impact category and may suggest to decrease their amount by applying technological changes to the process (e.g. use of de-sulphurized fuel). After the suggested changes have been implemented (or their adoption has been simulated) in the process, the analyst will recalculate the indicator under consideration and will assess the extent of the performance improvement. However, it is very likely that the suggested change affects other impact categories and, due to the reliance on the same set of input data, the improvement in one category might translate into a worse performance in another category (e.g. fuel de-sulphurization requires an additional technological process and increased energy input and generates additional waste to dispose of).

5. Conclusion

We presented in this paper a framework for a comprehensive investigation of complex systems. The joint application of several different methods to the analysis of technical and social systems based on the same set of inventory data allows a consistent reading of a system's performance and the comparability of calculated indicators. Some of the methods used are specific for local scale evaluation, while others are more suited for larger regional or biosphere scales. Moreover, the inclusion of the emergy synthesis approach provides the whole procedure with a built-in ability to take time and environment (biosphere, other species) into proper account. Investigating a system performance is by itself a very difficult task, due to the complexity of the problems that are always involved. When a simplified model is adopted, this is certainly a way to address part of the problem at the cost of leaving unsolved another part of it. Depending upon the goal of the investigation, this is sometimes a useful procedure. However, investigators very often run the risk of neglecting the complexity of the problem and taking their model as reality. As a consequence, they assign a value to a process product according to the results of their simplified investigation. The outcome of this evaluation process is then used in other subsequent evaluations and translated into economic and policy actions. In so doing, the complexity is lost: reality does not fit the model and the planned policy fails or is inadequate. We skip the simplified picture, by not forcing the investigation towards a monodimensional reading, i.e. by generating a set of performance indicators that are capable to answer to different questions at different scales. Limiting the investigation only to assessing the energy efficiency or to pointing out the contribution of a system to the global warming sends a misleading message to policy makers and managers. Instead, making it very clear that a system might perform very well under a specific point of view and much worse under another point of view or at a different scale calls for a policy making procedure that recognizes and combines different legitimate perspectives.

The proposed integrated approach aims at overcoming the limits of individual methods and generating the added value of a comprehensive picture for each process step, the process as a whole, the local scale and global scale environmental interactions, as well as for the thermodynamic process performance. Evaluating comparable alternatives necessarily requires the adoption of a multi-criteria approach, specially when specific answers regarding different possible uses of resources in the space–time frame of interest are sought. It must be realised that in virtually all cases there is no single 'optimal' solution to all problems. Only an analysis based on several complementary approaches can highlight the inevitable trade-offs that reside in alternative scenarios, and thus enable a wiser selection of the option embodying the best compromise in the light of the existing economic, technological and environmental conditions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2010.09.005.

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