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European Futures for Energy Efficiency

# The metabolism of Barcelona: characterizing energy performance across levels and dimensions of analysis at the city level

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**Deliverable 4.3**

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# History of changes

| HISTORY OF CHANGES | | |
|---|---|---|
| **Version** | **Publication date** | **Change** |
| 1.0 | March 2018 | Initial version |
| 2.0 | April 2019 | Update of tables to the latest version and minor changes to the methodology.<br>Revision in response to Project Review (Final Reporting Period):<br>- Inclusion of a short Executive summary<br>- A new figure (Figure 4-9) has been added in order to clarify the concept of commuter.<br>- Sections has been reorganized<br>- Correction of typos. |

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# Executive summary

## I.The issue to be explored

Deliverable 4.1 provides a critical appraisal of the concept of energy efficiency, it is simplistic for governance purposes and it should be replaced by the concept of energy performance compatible with the need of providing a richer characterization of the issue. Deliverable 4.2 proposes a solution to this problem: it introduces and illustrates the concept of *end use matrix*, an effective method to handle the complexity of the information required to provide an effective characterization of the performance of energy uses in society. Following in the same line, this deliverable (Deliverable 4.3) addresses two additional research questions related to the possible use of the end use matrix to characterize energy performance:

1. Whether it is possible to apply this innovative accounting method at the level of a city. This is an important point because the *end use matrix* could play a significant role in the booming field of analysis of urban metabolism. Moreover, by moving to a local level of analysis, the end use matrix allows the analysis of the implications of decisions related to the social practices expressed outside the market (e.g. leisure or caring activities taking place in residential or public space);
2. Whether it is possible to provide a characterization of the metabolic pattern of social-ecological systems not only in relation to assessments of energy metabolized per hour of human activity (studying the rate of metabolism) but also in relation to energy metabolized per unit of land use (studying the spatial density of the flows).

## II. What was done to investigate it

We selected a case study – the urban metabolism of Barcelona – and then we applied to this case study the conceptual approach used for the development and generation of end-use matrix at the national level done in Deliverable 4.2. The development of this application required a few adjustments to the original protocol originally developed for analysis carried out at the national level. Three important sources of differences are:

(1) The level of analysis is more localized and therefore, we had to adopt a more detailed set of categories of accounting in order to characterize structural and functional elements (e.g. activities inside the household sector);

(2) At the level of a city – especially in a city like Barcelona – quantities of human activity can not be assumed as just the one from the residents. This is because the important effect of the human activity associated with the presence of daily commuting workers living outside the city (50% of the working activity in the city) and of tourists (very important for the activities in the service sector) over the metabolism of the city;

(3) The analysis of land use (the spatial location of the metabolic structure) required a new approach to the categorization, especially when considering that in urban building the "area used" inside the apartments, does not coincide with the "land used" by the building. A multistory index had to be introduce to bridge the two assessments.

Addressing these new features of the analysis (compared with the national end use matrices) has required: (i) the development of a new and more elaborated protocol for the generation of the end use matrix; and (ii) the need of expanding the sources of data, moving from a consultation of easy to obtain national statistics to a hunting of a myriad of local data sources, some of which are only available in the form of grey literature. For this reason, we had also to consult with local experts in the local administration to clarify doubts, double check the reliability of estimations and plausibility of some assumptions.

## III. The method employed

The end use matrix is based on the application of the Multi-Scale Integrated Analysis of Societal Ecosystem Metabolism (MuSIASEM) accounting framework to the description of urban metabolic patterns.

## IV. The data and sources

As mentioned the identification and the tracking of the sources of data required for this assessment, should be considered as one major achievement (result) of this study. The explanation of the data and the sources is given in Appendix 1 (a 34 page document!). In which the various sources are listed and the relations over the data used for the assessments are explained.

## V. The results

*1. This deliverable presents a reproducible protocol of accounting based on the concept of energy end-use matrix to assess energy performance at city level*. The protocol allows identifying the factors determining the internal "end uses" of metabolized flows: ***who*** is using and ***how*** the flows, ***which*** flows, ***how much*** of each flow, defining characteristic benchmarks as flows per hour of human activity and per unit of area of built environment. It can be applied not only to energy, but also to other flows such as food, water, emissions or waste. This is an important achievement because due to the extreme degree of openness of cities it is difficult to get a clear idea of the relations between processes taking place inside the city and the processes taking place outside their administrative borders for providing the required supply of energy carriers.

*2. This deliverable defines and tests the possibility of gathering the data required by the protocol*. The analysis of city metabolism requires many different typologies of data from many different sources, which then need to be combined in a coherent and meaningful way to fill all the cells of the energy end-use matrix. Data requirements for the implementation of the accounting protocol and the possibility of gathering them were tested for the city of Barcelona.

3. This deliverable illustrates the potentiality of the end-use matrix approach for studying the energy performance at city level. The end-use matrix approach provides benchmarks describing the energy performance and size of the various functional elements (e.g., port, transportation, air conditioning). It makes it possible to scale the quantitative information referring to either a functional or a structural element in relation to the city metabolism as a whole (i.e. contextualize the relative importance of particular energy efficiencies over the whole system). It tells how much the different end uses determine the overall metabolic picture of the city. For instance, how important is the activity of the port in determining its overall energy metabolism. The values of benchmarks for typologies of functional and structural elements allows an informed comparison with other cities that have different mix of functional and structural elements reflecting differences in relation to the weather, mix of economic activities, size of population, residential characteristics, etc. Moreover, the level of redundancy implied by the accounting method, the so called “Sudoku effect”, makes it possible to identify problems in relation to the availability of data and/or missing relevant information. Finally, the self-explanatory set of relations used for building the end-use matrix represents a transparent and transdisciplinary analytical tool – it shows openly how the quantitative assessments are obtained – and therefore can be used to co-produce energy policies or knowledge about the performance of the city in a participatory and inclusive way.

## VI. The significance of results for policy-makers (governance)

After examining the Covenant of Mayors, an initiative promoted by the EU and signed by more than 6800 cities in 57 countries we identified three systemic problems that could be solved by the application of the end-use matrix. (1) The definition of generic objectives (e.g., “reduction of emissions” or “increase in renewable energy”) is simplistic and difficult, if not impossible, to translate into specific policy targets across different cities. (2) The targets of the CoM have no sense when defined per capita due to the importance of commuters and tourist in their performance, and when just looking absolute emissions/consumptions without considering the activities or structural changes in the cities. (3) The assessment of emissions faces a systemic epistemological problem in that it has to deal with direct, indirect, and embodied emissions in consumption. This requires addressing the co-existence of non-equivalent views of the metabolism: *the state* (what happens inside the city) and *the pressures* (what happens elsewhere to guarantee the supply and the sink capacity associated with the ability of metabolize the flows). The main message for policy makers is that the current problem-formulation and existing methods have serious shortcomings for providing a meaningful analysis of ‘sustainable city metabolism’. They could do better when choosing scientific evidence.

After examining two specific plans in Barcelona related to energy and climate: *Energy Improvement Plan* (PMEB) and *Energy, Climate Change and Atmospheric Quality Plan* (PECQ) we identified 3 systemic problems that could be solved by the application of the end-use matrix: (1) an abundant amount of detailed and relevant information is available for the city of Barcelona, but these data are not organized or used in a coherent way, within an integrative framework across different levels of analysis and dimensions; (2) within the elements determining the metabolic pattern of Barcelona we found a heterogeneity of specific situations and specific issues requiring specific solutions and specific policies. A ‘one size fits all’ solution for the sustainability problems of different cities simply does not exist; (3) the discussion about sustainability and notably changes in the energy end uses of Barcelona has a strong political dimension. Sustainability can be interpreted as a technical or political issue, or both. Ignoring the political option of changing social practices and looking only at the political option of adding new technical gadgets to stabilize the status quo may lead to both bad analyses and bad policies. The main message for policy makers is that a more effective multi-level integrated assessment based on participatory approach to the characterization of the performance of cities, looking at different dimensions and implications, is required.

## VII. The significance of results for stakeholders (reflexivity on what “we” want to be)

The example of application of the end use matrix to the analysis of the metabolic pattern of Barcelona clearly shows that this approach makes it possible to adopt participatory approaches in order to check the quality of the narratives used to frame sustainability problems and to check the quality of the quantitative information used to inform the process of decision making. Stakeholders have to ask both decision makers and scientists that more effective tools be used to inform the debate on energy policies.

## VIII. The significance of results for other researchers (plausibility scientific inquiry)

Given the rapid proliferation of complicated models, methods, and sustainability targets that need monitoring, the most effective strategy for generating sustainability indicators may well be completely abandoning the dream of developing simple ‘evidence-based’ quantitative indicators.

(i) When using generic targets at the local scale (e.g. efficiency of transportation in terms of MJ per ton-km), no simple relation can be established between the effects achieved at the local scale and the effect that this change will imply at the level of the city as a whole;

(ii) When using generic targets at the large scale (e.g. the city as a whole), it is difficult to know the implications of the achievement of these targets in relation to different attributes of city performance: quality of life, employment, emissions, economic growth, land use, etc. For example, a radical cut of the supply of fuels and electricity would be the most efficient strategy to dramatically reduce emissions at city level, but nobody would propose this solution to solve sustainability problems. Trade off analysis and compromise decisions are required.

(iii) Cities are open systems and the phenomenon of externalization makes any assessment of their energy performance tricky. Constructing indicators that ignore the fact that consumption and emissions depend on import/export may incentivize the adoption of cost-shifting strategies.

The main message of this deliverable is that it is possible to apply insights from the field of complexity theory to generate an information space based on relational analysis that can handle the epistemological challenges of multi-scale and multi-disciplinary assessment. The proposed approach has great potential for improving the quality of the process used to produce and use quantitative information to be used for deliberation over sustainability policies.

Not only the end-use matrix represents an innovative analytical tool because of its ability of bridging quantitative information across different levels of analysis but it also makes it possible to avoid other limits of conventional quantitative analysis:

1. Moving away from mono-scale and mono-dimensional analysis (“energy efficiency” of a city), toward multi-scale and multi-dimensional analysis (“energy performance” of a city);
2. Moving away from predicative representations, deterministic results that must be uncontested in relation to both definitions and assumptions in order to be usable, toward impredicative representations, contingent results depending on the choice of definitions and assumptions that can be deliberated in participatory processes;
3. Moving away from models providing representations chosen by the analysts, toward an approach generating representations coproduced with the users of the analysis;
4. Moving away from “dead quantitative assessments done once and for all”, toward “living and flexible information spaces used for co-production of knowledge”

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# Abbreviations

AEB – *Agència de l'Energia de Barcelona* – Energy Agency of Barcelona

AMB – *Àrea Metropolitana de Barcelona* – Metropolitan Area of Barcelona

BEI – Baseline Emission Inventory

BU – Building Use

CoM – Covenant of Mayors

dS – total entropy change

dSi – entropy production in a system

dSe – entropy flux due to exchanges between the system and the environment

$EC_j$ - Energy Carriers (i = electricity, heat or fuel)

$EJP_i$ – Economic Job Productivity – Quantity of GVA per hour of Human Activity in *i*

Elec – Electricity

$EMR_i$ – Exosomatic Metabolic Rate – Quantity of Energy Carrier *j*

$EMD_i$ – Exosomatic Metabolic Density – Quantity of Energy Carrier *j*

ES – Energy Sector

$ET_{ij}$ – Energy Throughput – Quantity of Energy Carrier *j* metabolized per year in *i*

$EU_i$ – End $Use_i$ – A profile of quantities of Human Activity and Energy Carriers in *i*

EU ETS – EU Emissions Trading System

$EUSP_i$ – Economic Useful Surfaces Productivity – Quantity of GVA per area of Useful Surfaces in *i*

GER – Gross Energy Requirement

GHG – Greenhouse Gases

$GVA_i$ – Gross Value Added (average year) in the compartment *i*

$HA_i$ – Human Activity (average year) in the compartment *i*

LCE – Leisure, Commerce and Education

LU – Land Use

MC – Manufacturing and Construction sector

MEI – Monitoring Emission Inventory

MuSIASEM - Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism

PES - Primary Energy Sources

PMEB – *Plan de Mejora Energética de Barcelona* - Energy Improvement Plan

PECQ – *Pla de l'Energía, Canvi climàtic i Qualitat de l'aire de Barcelona*- Energy, Climate Change and Atmospheric Quality Plan

OOA – Other outdoor activities

OPW – Outside Paid Work

PW – Paid Work

$SD_i$ – Administrative area of *barrio i*

SEAP – Sustainable Energy Action Plan

TET – Total Energy Throughput

TOE – Tonnes of Oil Equivalent

US – Useful Surfaces

VA – Value Added

# Units and key concepts

TJ – Tera Joules ($10^{12}$ J)

GJ – Giga Joules ($10^{9}$ J)

MJ – Mega Joules ($10^{6}$ J)

## The MuSIASEM approach

**MuSIASEM** or **Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism** is a transdisciplinary approach developed for studying sustainability issues building on energetics, biophysical economics using insights from complexity such as relational analysis, cybernetics, semiotics, hierarchy theory and general systems theory. The approach was introduced by Mario Giampietro and Kozo Mayumi at the end of the 90s and it is under continuous development.

The multiscale and transdisciplinary approach proposed by MuSIASEM uses relational analysis for the quantitative assessments considering diverse potentially relevant types of expertise, legitimate interest and concern when informing policy making. MuSIASEM can be used as a decision support tool for diagnostic evaluation or option space exploration in a transparent way. Sustainability of social-ecological systems can be evaluated in relation to three complementary key aspects:

(i) Feasibility - the compatibility with processes outside human control taking place in the biosphere (external biophysical constraints);
(ii) Viability - the compatibility with process under human control in the technosphere as available technologies or the existence of adequate social practices;
(iii) Desirability – the compatibility with normative values and institutions such as cultural traditions, established social practices or preferences.

MuSIASEM has been used in the EUFORIE project to provide a critical appraisal of the actual framing of the concept of efficiency in political and scientific arenas from a conceptual and practical point of view. We propose an alternative conceptual tool: the End Use Matrix, which breaks down silos and prevents the most powerful actors from cherry picking the specific output/input ratios, among the many possible indicators of energy efficiency, that best matches their agenda. To achieve the goals of saving energy and associated environmental impacts such as emissions of GHG, efficiency policies should be based on effective indicators establishing a clear relation between the local performance of energy uses and absolute energy consumption, i.e. global performance of the whole network of energy conversions. Establishing this relation requires developing a system of accounting capable of maintaining coherence across scales and dimensions of analysis while combining different metrics.

***For more about MuSIASEM, see:***

*Giampietro, M. and Mayumi, K. 1997. A dynamic model of socioeconomic systems based on hierarchy theory and its application to sustainability. Struct. Chang. Econ. Dyn. 8, 453–469. https://doi.org/10.1016/S0954-349X(97)00017-9*

*Giampietro, M., Mayumi, K., Sorman, A., 2012. The Metabolic Pattern of Societies: Where Economists Fall Short. Routledge, New York.*

*Giampietro, M., Mayumi, K., Sorman, A.H., 2013. Energy analysis for a sustainable future: multi-scale integrated analysis of societal and ecosystem metabolism. Routledge, New York.*

## The End Use Matrix

The end use matrix is a MuSIASEM tool that integrates information on where, how, how much, which type, who and why biophysical funds and flows are used in a socio-economic system. The analysis is not deterministic but still it makes it possible to generate contingent evaluation of the viability of alternative profiles of allocation of human time or other resources, in relation to a set of functions to be expressed by society. It organizes quantitative information referring to different end uses described across different levels of analysis (whole society, sectors, sub-sectors). It follows the fund-flow scheme of Geoergescu-Roegen, where flows are quantities appearing or disappearing over the period of the analysis: energy, money, water, etc., and funds are structural elements preserving their identity: workers, technical capital, land use.
An end use is defined as the specific profile of inputs required to achieve a specific task. In the simplified definition adopted in this example, considering energy inputs only, the expected profile of inputs required for achieving a given task i can be represented using a vector:

$$[HA_i,\ EMR_{electricity i},\ EMR_{heat i},\ EMR_{fuel i},\ ET_{electricity i},\ ET_{heat i},\ ET_{fuel i}\ ]$$

where:

**$HA_i$** - Human Activity allocated in hours/ year (h);

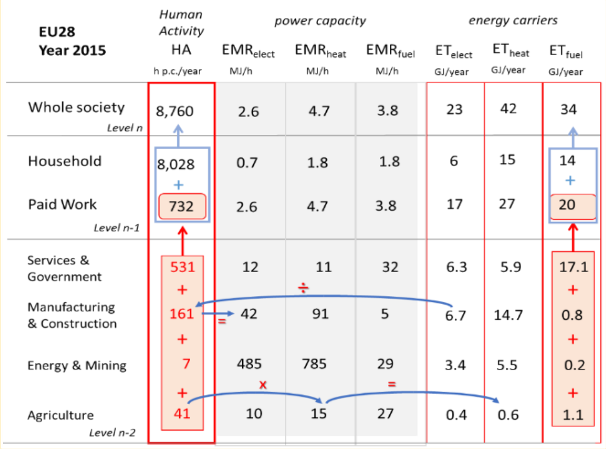
**$ET_{ji}$** - Energy throughput metabolized in the form of energy carrier j. In this case the index j refers to electricity, heat or fuel, in joules/year (J);

**$EMR_{ji}$** –Exosomatic Metabolic Rate: the amount of energy carriers metabolized per human activity, measured in joules of $EC_j$ per hour of $HA_i$ (J/h) for the different typologies of energy carrier. It is a proxy of use of technical capital.

The combination of extensive variables ($HA_i$ and $ET_i$ ) and intensive variables ($ET_i/HA_i$ – $EMR_i$) in different levels generates redundancy in the information space because of three basic congruence constraints, what is called a sudoku effect:

#1 $(\sum ET_i)_{level\ n-1} = ET_{j\ level\ n}$;  #2 $(\sum HA_i)_{level\ n-1} = HA_{j\ level\ n}$;  #3 $HA_i \cdot EMR_i = ET_i$

This entails impredicative relations. What society wants to satisfy human needs defines a downward causation, whereas the effects of the constraints determined by a limited amount of resources, technology or labor, generates an upward causation. This defines the option space within which political decisions can stir the metabolic pattern.



| EU28<br>Year 2015 | Human Activity<br>HA<br>h p.c./year | EMR$_{elect}$<br>MJ/h | EMR$_{heat}$<br>MJ/h | EMR$_{fuel}$<br>MJ/h | ET$_{elect}$<br>GJ/year | ET$_{heat}$<br>GJ/year | ET$_{fuel}$<br>GJ/year |
|---|---|---|---|---|---|---|---|
| | | power capacity | | | energy carriers | | |
| Whole society<br>*Level n* | 8,760 | 2.6 | 4.7 | 3.8 | 23 | 42 | 34 |
| Household | 8,028 | 0.7 | 1.8 | 1.8 | 6 | 15 | 14 |
| Paid Work<br>*Level n-1* | 732 | 2.6 | 4.7 | 3.8 | 17 | 27 | 20 |
| Services & Government | 531 | 12 | 11 | 32 | 6.3 | 5.9 | 17.1 |
| Manufacturing & Construction | 161 | 42 | 91 | 5 | 6.7 | 14.7 | 0.8 |
| Energy & Mining | 7 | 485 | 785 | 29 | 3.4 | 5.5 | 0.2 |
| Agriculture<br>*Level n-2* | 41 | 10 | 15 | 27 | 0.4 | 0.6 | 1.1 |

The definition of an end use matrix allows a non-deterministic analysis of the constraints affecting the allocation of human activity on a set of competing functional compartments of the society – i.e. there is a chicken-egg relation over the values taken by the numbers in the matrix. The analysis is not deterministic but still it makes it possible to generate contingent evaluation of the viability of alternative profiles of allocation of human time or other biophysical resources, in relation to a set of functions to be expressed by society.

***For more about the End use Matrix see:***

*Velasco-Fernández, R., Giampietro, M., Bukkens, S.G.F., 2018. Analyzing the energy performance of manufacturing across levels using the end-use matrix. Energy 161, 559–572.*

## The Sudoku Effect

Sudoku is a logic-based number placement puzzle consisting in a 9x9 grid with digits so that each column, row and each of the nine 3x3 sub-grids that compose the grid, contains all the digits from 1 to 9. The column, row and block constraints generate mutual information within the information space of the sudoku grid. As a result, each time a number is introduced in the grid a path dependency is generated, and the option space of viable patterns is reduced. The sudoku game provides a very direct example of how relational analysis – the pre-analytical definition of expected relations over the values that will be taken by numbers in a specified grammar – can be used to generate an impredicative effect within an information space. A sub-critical Sudoku, in which the written numbers still does not fully define the missing ones, is an example of set of quantitative relations that is not deterministic, but still providing enough mutual information to generate expected patterns (Giampietro and Bukkens, 2015).

**In MuSIASEM, the Sudoku effect** refers to the mutual information generated when building a multi-scale and multi-dimensional set of relations over the quantitative assessments of flows and flow-fund relations. This mutual information generates constraints determined by the impredicative relation between top-down and bottom-up information. Therefore, aggregated data from statistical sources must be consistent with technical data about the processes described at lower hierarchical levels. The Sudoku effect makes it possible to apply systematically what is called triangulation in evaluation science, a "*research technique that facilitates the cross-verification using more than two sources. In particular, it refers to the application and combination of several research methodologies in the study of the same phenomenon […]. By combining multiple observers, theories, methods, and empirical data, researchers aim at overcoming the weaknesses, intrinsic biases and the problems that are often found in single method, single-observer and single-theory studies*." (Carugi, 2016).

When describing the metabolic pattern of a society with MuSIASEM we can characterize the various activities of both production and consumption in the form of a data array. The data are composed both of extensive variables – quantities of energy of different forms and quantities of human activity – and intensive variables – ratios of quantity of energy per unit of human activity. The need of reaching congruence across the values describing the metabolic pattern across different levels of analysis becomes extremely transparent in the organization of data in the end use matrix (see the box presenting the end use matrix).

***For more about the Sudoku Effect see:***

*Giampietro, M., Bukkens, S.G.F., 2015. Analogy between Sudoku and the multi-scale integrated analysis of societal metabolism. Ecol. Inform. 26, 18–28.*

# Technical summary

In this deliverable we show that the *energy end-use matrix*, described in theoretical terms in D4.1 and applied to the national level in D4.2, can also be used to inform the debate about energy performance at *city level*. We illustrate in detail how the multi-level end-use matrix can be adapted and applied to the analysis of energy performance at city level, using Barcelona as case study adopting the rational of "metabolism of a city" – i.e. in order to reproduce their structures and express their functions cities must use an expected pattern of material and energy inputs that they transform into emissions and wastes. In particular, the work presented in this deliverable has pursued three objectives:

## Objectives

a. *Define a reproducible protocol of accounting based on the concept of energy end-use matrix to assess energy performance at city level*. The extreme degree of openness of cities poses challenges to the application of the energy end-use matrix at city level. Cities rely heavily on processes taking place outside their administrative borders for their energy (and food) security and they are organized in different functional elements (e.g. residential sector, mobility sector, healthcare sector) using structural elements (e.g. houses, appliances, buses, metro and hospitals) to express different functions at the local scale. This complex organization makes it difficult to identify the factors determining the consumption of energy carriers. For this reason, the proposed protocol for an energy end-use matrix is based on the 'triangulation' of quantitative information from different data sources across different hierarchical levels of analysis. The city energy end-use matrix combines information coming from: (i) different extensive variables (statistics) describing the size of flow and fund elements on a yearly basis (energy carriers, human activity, land uses) at different levels; (ii) different intensive variables (technical coefficients) quantifying consumed flows per unit of fund elements (metabolic rates per hour of human activity, metabolic densities per unit of area) at different levels. Intensive variables represent the expected characteristics of performance (benchmarks) of the functional and structural elements of the system.

2. *Define and test the data requirements for the protocol*. The analysis of city metabolism requires many different typologies of data from many different sources, which then need to be combined in a coherent and meaningful way to fill all the cells of the energy end-use matrix. Data requirements for the implementation of the accounting protocol were tested for the city of Barcelona. Energy end-uses were characterized for all relevant socio-economic activities (the paid-work sector and its sub- and sub-sub-sectors, and the 'non-paid-work sector' including activities at home, commuting, tourism, leisure and education, and use of other city services). Specifically, the characterization of the identified set of energy end-uses across levels and dimensions

required data on human time allocation (for three population categories: residents, commuters, and tourists) and use of energy carriers (distinguishing among three categories of energy forms: electricity, heat and fuels). The energy end-use matrix requires a substantial amount of data and while most data are available, they are not always easily accessible or only accessible at a too-aggregated level.

3. *Apply the protocol and evaluate the potential of the energy end-use matrix for studying the energy performance at city level*. Following definition of the protocol and data requirements and data collection, the tool was applied to the analysis of the energy metabolism of Barcelona. The end-use matrix obtained provides 'benchmarks' describing the energy performance and size of the various functional elements (e.g., port, transportation, air-conditioning). The relevant feature is that the organization makes it possible to scale the quantitative information referring to either a functional or structural element in relation to the city metabolism as a whole. It tells how much the different end uses determine the overall metabolic picture of the city. For instance, in Barcelona the port is an important determinant of the overall energy metabolism. The organization of the end use matrix makes defining specific benchmarks for typologies of functional and structural elements is very useful for analysis and comparisons with other cities that have different mix of functional and structural elements reflecting differences in relation to the weather, mix of economic activities, size of population, residential characteristics. Moreover, the level of redundancy implied by the accounting method (the so called Sudoku effect) makes it possible to identify problems in relation to the availability of data and/or missing relevant information. Finally, the self-explanatory set of relations used for building the end-use matrix represents a transparent and transdisciplinary analytical tool that can be used to co-produce knowledge about the performance of the city in a participatory and inclusive way.

## Main Findings

The contents of this deliverable have been organized in five sections, the main findings of which are summarized below:

*Section 1. How robust and effective are narratives, targets and strategies for sustainable cities in the EU?* In this section we identify the problems with existing generic protocols for defining indicators of efficiency and policy targets for cities. In particular, we examine the Covenant of Mayors, an initiative promoted by the EU and signed by more than 6800 cities in 57 countries, and carry out a critical appraisal of its narratives, analytical tools and formulation of objectives. We identified three problematic issues:

i. The definition of generic objectives (e.g., reduction of emissions or increase in renewable energy) is simplistic and difficult, if not impossible, to translate into specific policy targets across different cities. When dealing with a wide diversity of typologies of cities, biophysical contexts and historical situations (e.g., transitional periods) it is impossible to have a single indicator providing the required information for guiding policy;

ii. The assessment of emissions faces an epistemological problem in that it has to deal with direct, indirect, and embodied emissions (embodied in the inputs consumed);

iii. Measuring the metabolic characteristics of an open system, operating simultaneously across different hierarchical scales, is extremely complex. Quantitative results necessarily depend on the pre-analytical assumptions (that reflect the purpose of the analysis). The issue of sustainability requires the simultaneous consideration of different relevant criteria of performance; the use of a single protocol to assess overall indicators of the type 'one size fits all' simply does not make sense.

The main message of this section is that the current problem-formulation and existing methods have serious shortcomings for providing a meaningful analysis of 'sustainable city metabolism'.

*Section 2. Energy and climate change agenda of Barcelona*

In this section, we examine the problems encountered with the implementation of two specific plans in Barcelona related to energy and climate: *Energy Improvement Plan* (PMEB) and *Energy, Climate Change and Atmospheric Quality Plan* (PECQ). The following two lessons learnt are particularly relevant:

i. An abundant amount of detailed and relevant information is available for the city of Barcelona, but these data are not organized or used in a coherent way (within an integrative framework across different levels of analysis and dimensions);
ii. Within Barcelona we found a heterogeneity of specific situations and specific issues requiring specific solutions and specific policies. This clearly indicates that policy advice and suggestions for best practices need always be contextualized in relation to the specificity of the problems found in different cities. A 'one size fits all' solution for the sustainability problems of different cities simply does not exist;

The discussion about sustainability (and notably changes in the energy end uses of Barcelona) has a strong political dimension. Sustainability can be interpreted as a technical or political issue (or both). We can imagine to develop new technology to keep existing behaviors and institutions (the popular technical solutions pushing for a continuous supply of innovations), or we can imagine to change behaviors and institutions (the political solution) to solve our problems of sustainability using existing technology.

Ignoring the political option and framing policies only in terms of technical targets may lead to both bad analyses and bad policies.

The main message of the section is that the experience done so far in Barcelona supports the claim that a more effective multi-level integrated assessment based on participatory approach to the characterization of the performance of cities is required.

*Section 3. An application of relational system analysis to the metabolic pattern of energy in Barcelona.* In this section we identify and present the theoretical concepts underlying the development of the analytical tool (the energy end-use matrix) and illustrate their usefulness in the different solutions adopted to generate the quantitative representation of the metabolic pattern of cities. Barcelona is used as an example. This section covers:

i. *Identification of the aspects of city metabolism relevant for a quantitative assessment of its energy performance*. Building on the discussion in Section 1, it is shown that the performance of a complex set of processes – the metabolism of a city– cannot be described and handled by a simple system of monitoring and control. Simple indicators such as overall ‘energy use’, overall ‘emissions’, or input/output indexes used out of context are not sufficient to represent the complexity of the metabolic pattern. An effective analytical tool kit must have adequate power of discrimination to identify relevant characteristics of the energy metabolism across different scales and different dimensions of analysis: What types of energy carriers are used and how much of each is used? Who is using them, where, when, how and why? Without fully characterizing all these facets for the entire set of energy transformations taking place in a city it is difficult to produce sound quantitative assessments for informing policy. To achieve meaningful results, some golden rules must be observed: (i) proper handling of different energy metrics; (ii) generation of an information space describing *who* is using *what type* of energy carriers and *how much*, and *how* and *why* they are being used; (iii) proper handling of the co-existence of non-equivalent types of data (e.g., spatial versus alfa-numerical data).
ii. *Explanation of the theoretical concepts derived from complexity theory underlying the analysis (with practical examples from the analysis of the metabolic pattern of Barcelona)*. It is shown: how to use the rationale of non-equilibrium thermodynamic to study sustainability; how to use the concept of *holon* to analyze the relation between material and immaterial (functional/notional) elements in complex metabolic systems; how to use basic concepts of relational system analysis to move across quantitative assessments referring to different dimensions and scales.
iii. *Illustration of the solutions adopted in the development of the novel analytical tool*: The importance of using a semantically-open procedure to organize quantitative assessments for cities operating in different contexts and situations;

How to use the end-use matrix as a tool-kit addressing the different aspects of sustainability of the energetic metabolic pattern (direct, indirect, and embodied consumptions/emissions); and contextualizing indicators of performance across different typologies of cities.

The main message of this section is that novel theoretical concepts from complexity science are extremely useful (if not essential) to develop more effective assessments of city metabolism.

*Section 4. Implementing the energy end-use matrix for the city of Barcelona*. This section covers the following aspects:

i. An introductory quantitative description of the relevant attributes of Barcelona in relation to climate, population, demographic structure, economic characteristics, level of imports/export, industrial infrastructures (notably the port) and infrastructures of the energy sector;
ii. Explanation of the structure and data organization inside the end-use matrix and the organization of data sources. The various approaches and data sources used to calculate the values for the cells of the end-use matrix are listed and explained (a detailed description is available in Appendix 1);
iii. Illustration of the relations among human time (activity) allocation across different categories of accounting; explanation of how to assess the origin of human activity (residents, commuters or tourists) in relation to end-uses. How much and whose time is invested in the various (sub-)sub-sections of the paid work sector and dedicated to the various activities taking place outside the paid work sector?
iv. Illustration of the relations among land-uses across the different categories of accounting defined for the Built Environment of Barcelona. How to handle the three co-existing categories of accounting areas: external land use, internal building use, and administrative units (such as districts and *barrios*);
v. Illustration of the relations among use of energy carriers across different categories of accounting. Identification of the various external referents (i.e., cars, trucks, trains, metro, heating systems, home appliances) used to estimate the consumption of energy carriers in the various end-uses considered;
vi. Illustration of the relations among the gross added value across different categories of accounting. The analysis of economic flows is important because it establishes a link between the biophysical reading provided by the end-use matrix and the classic economic reading.

The main message of this section is that it is possible to construct and populate with data an energy end-use matrix for a complex and open city like Barcelona.

*Section 5. Results of the exploratory application of the end-use matrix to the analysis of the energy metabolism of Barcelona*. Because of the nature of this exercise – exploring the potentiality of a new analytical tool we have two types of results:

**Methodological results:**

The methodology proposed in this deliverable is innovative in that it moves away:

i. from the concept of ‘energy efficiency’ of a city toward the concept of ‘energy performance’ of a city;
ii. from a mono-scale mono-dimensional quantitative analysis of efficiency toward a multi-scale multidimensional quantitative analysis of performance;
iii. from predicative representations (deterministic results) toward impredicative representations (contingent results);
iv. from models providing representations chosen by the analyst toward an semantically-open approach allowing representations chosen by various users of the analysis;
v. from “dead quantitative assessments done once and for all”, toward “living and flexible information spaces used for co-production of knowledge”

**Quantitative Results:**

(i) Examples of multi-level end-use matrix: (1) the characterization of end-uses at the level n (whole Barcelona) is split, at the level n-1 into two characterizations of end uses referring to two main functional categories of human activity: Outside Paid Work and Paid Work. Each one of these two characterizations of end uses is further divided, at level n-2, into lower-level characterizations of end uses referring to lower level categories of human activity. Outside Paid Work is divided into Residential, Mobility, Use of Services and Government, Other Outdoor activities; whereas Paid Work is split into Services and Government, Port, Manufacturing and Construction, Energy Sector. (2) the characterization of end-uses at a lower-level analysis goes from level n-2 (in relation to the functional category of human activity Paid Work) to level n-3 (describing the metabolic pattern of the Service and Government sector of Barcelona excluding transport). (3) the characterization of end-uses at a lower-level analysis goes from the level n-2 (in relation to the functional category of human activity Paid Work) to level n-3 (describing the metabolic pattern of transport inside the Service and Government sector of Barcelona);

(ii) Examples of characterization and analysis of the various functional compartments at the level n-3 by studying the coupling of structural elements to functional elements – e.g. identification of the structural elements (trams, buses, metro, taxies, trains) included in the functional category Public Mobility or the structural elements (quantity and types of students in kindergartens, primary schools, high schools, bachelors, universities);

(iii) Examples of comparison of metabolic characteristics of functional elements at the level n-3 – e.g. comparison of end-uses at a lower level of analysis per typology of activity. This analysis provides benchmarks of consumption of electricity, heat and fuels per hour of work in the different sectors of Paid Work – restaurants, education, health-care, public transportation;

(iv) Examples of economic characteristics associated with metabolic characteristics of functional elements at the level n-3. Data on the metabolic characteristics of sectors can be complemented by data relevant for socio-economic analysis such as – hours of labor (related to employment) and gross value added generated per hour in the different sub-sectors considered – e.g. construction, manufacturing, services;

(v) Examples of characterizations referring to spatial analysis of residential used to study the effects of different factors on the metabolic characteristics of land use categories – i.e. size of the house (area of the household), amount of area per person, household income, year of construction of the buildings;

The options available for the calculation of emissions, including direct, indirect and embodied emissions, are illustrated.

Finally, possible applications of the end-use matrix include the development of a software available through an interactive website that can be used to sustain a permanent process of quality control of the information (using the same rationale of Wikipedia) that can be used by the administrations of cities to generate a more robust knowledge of its own metabolic pattern. This collaboration should made possible a standardized characterization of the metabolic pattern of cities based on the concept of the multi-level end use matrix. Using this website different cities of the world would be able to share their experiences about: (i) analytical tools - how to analyze and how to improve their energetic performance; and (ii) best practices - how to solve practical problems by studying the efficacy of specific functions in relation to specific final cause (contextualized problems) and of specific structural elements in relation to specific functions (specific technical problems); (iii) policies – how to assess the effectiveness of applied policies in relation to the expected results.

*The main message of this section is that the proposed approach has great potential for improving the quality of the process used to produce and use quantitative information to be used for deliberation over sustainability policies.*

Last but not least the section of results present a short discussion of the problems experienced with the application of this methodology: (i) the requirement of a large amount of data not easy to obtain; (ii) the requirement of co-production with the various offices collecting data and generating statistics, in order to guarantee the congruence of quantitative data in the multi-level multi-dimensional analysis; (iii) the requirement of co-production with the users of the result, in order to guarantee a shared agreement on the pre-analytical definitions and the assumptions used in the implementation of the analysis. In relation to this point, it should be noticed that in this application we did not generate a co-production and that therefore our results are only relevant to illustrate the methodology and not as an input for policy.

## Policy summary

### Key Message

This deliverable explores a new methodology for characterizing and monitoring the energy performance of cities and generating quantitative indicators useful for informing policy. The *energy end-use matrix* is a novel tool for quantitative analysis of the energy metabolism based on complex system thinking. It integrates heterogeneous inputs of information, recognizing that co-existing multiple dimensions and multiple scales of analysis are relevant for the study of energy performance at city level. The tool is validated using the city of Barcelona as a case.

### Diagnosis: the problem with existing analyses of 'energy efficiency' of cities

*1. Setting generic 'targets' (e.g., a 30% reduction in 'emissions') without a discussion of the implications of the pre-analytical decisions required to make such an assessment (definitions, assumptions, scale and context to be considered) is a simplistic solution because it is impossible to identify in this way relevant indicators for guiding policy. In fact:*

(i) When using generic targets at the local scale (e.g. efficiency of transportation in terms of kcal per tonne-km), no explicit relation can be established between the effects achieved at the local scale and the performance of this change at the level of the city as a whole;

(ii) When using generic targets at the large scale (e.g. the city as a whole), it is impossible to know the implications of the achievement of these targets in relation to different attributes of city performance (e.g. quality of life, employment, emissions, economic growth, land-use). For example, a radical cut of the supply of fuels and electricity would be the most efficient strategy to dramatically reduce emissions at city level, but nobody would propose this solution to solve sustainability problems.

(iii) Cities are open systems and the phenomenon of 'externalization' makes any assessment of their energy performance tricky. Constructing indicators that ignore the fact that consumption and emissions depend on the level of import/export may incentivize the adoption of cost-shifting strategies.

2. *An analysis of city metabolism must be based on a complex information space*. Metabolic patterns are determined by two sets of conversions that are qualitatively different: (i) catabolism: the *production* of energy carriers (primary energy sources → energy carriers) for use by the city for expressing its functions; and (ii) anabolism: the *consumption* of energy carriers (energy carriers → end uses) by the city for expressing its

functions. These two sets of conversions require distinct accounting methods and models. Therefore, the analysis of city energy performance has to be based on the integration of different models and indicators in relation to a set of different targets. The overall assessment of the effects of the metabolic pattern of the whole city must include different criteria of performance, such as local emissions, global emissions, use of renewable energy, reduction of consumption, reduction of economic costs, effects on the quality of life of the citizen. An analysis of the energy performance of a city has to be carried out across different scales and different criteria.

3. *An integrated assessment of the energy performance of cities requires a transparent information space for deliberation*.

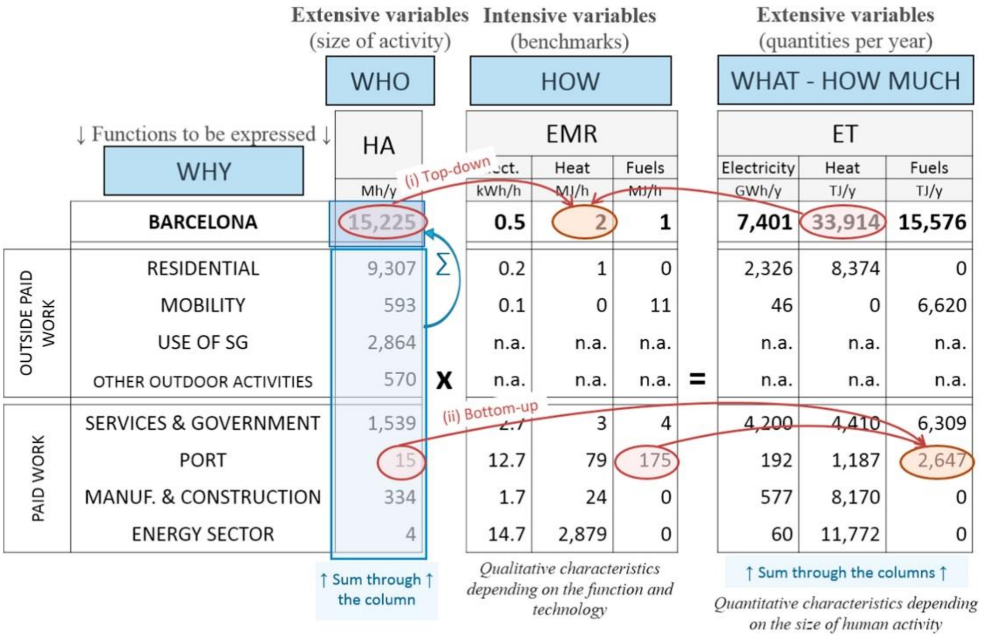
The calculation of the emissions of a city is not a straightforward operation. There are different categories of emissions: direct emissions, indirect emissions, embodied emissions in direct inputs (e.g. emissions from the power plants outside the city producing the electricity consumed in the city), and embodied emissions in indirect inputs (e.g. emissions from the energy consumed in the production of food in rural areas that is destined for consumption in the city). In this context, the definition of system boundaries is extremely important in the determination of the results and therefore it should be transparent. The boundary definition is a required pre-analytical decision in any quantitative analysis and determines what should and what should not be considered embodied in the inputs imported by the city. For this reason, the boundary definition is tricky and unavoidably contested. Depending on the purpose of the analysis or the chosen protocol, boundary definitions may have to be changed. Therefore, what should be included in the calculation of emissions is always an open decision and the decision may be different for assessments of $CO_2$ emissions, local pollutants (relevant for the air quality of the city) or GHG emissions (including other gases besides $CO_2$ relevant for the atmosphere).

### The multi-level energy end-use matrix as a possible solution to existing problems

Given the rapid proliferation of complicated models, methods, and sustainability targets that need monitoring, the most effective strategy for generating sustainability indicators may well be completely abandoning the dream of simple ‘evidence-based’ quantitative indicators. It will be more productive to move to a participatory procedure of co-production of knowledge in which social actors learn by doing how to identify, monitor and control relevant aspects of the city metabolism. For this task we need a flexible integrated characterization of the different end-uses associated with the energy metabolism of a city, providing a core of data covering all the relevant factors to be considered in a policy discussion. This can be achieved only through a participatory discussion of both the indicators used for the definition of targets and the methods of calculation of the data required for monitoring the situation. After having reached a consensus on how to obtain this integrated characterization it will become possible to generate a family of attributes and targets leading to the choice of an integrated set of indicators of performance.

The energy end-use matrix represents a useful tool to tackle the problems discussed so far providing a more effective input of information for policy by organizing the data on different categories of data describing the systems across different scales and dimensions of analysis. More specifically it organizes the quantitative information on the performance of the energetic metabolic pattern of cities providing a set of policy relevant pieces of information: who is using energy, what type of energy carriers are used, how much energy carrier is used per each type, how are energy carriers used and why.

An overview of the organization of the quantitative representation proposed in our analytical tool-kit is provided in Figure 0-1.



| | ↓ Functions to be expressed ↓ WHY | HA Mh/y | EMR ct. kWh/h | EMR Heat MJ/h | EMR Fuels MJ/h | ET Electricity GWh/y | ET Heat TJ/y | ET Fuels TJ/y |
|---|---|---|---|---|---|---|---|---|
| | BARCELONA | 15,225 | 0.5 | 2 | 1 | 7,401 | 33,914 | 15,576 |
| OUTSIDE PAID WORK | RESIDENTIAL | 9,307 | 0.2 | 1 | 0 | 2,326 | 8,374 | 0 |
| | MOBILITY | 593 | 0.1 | 0 | 11 | 46 | 0 | 6,620 |
| | USE OF SG | 2,864 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| | OTHER OUTDOOR ACTIVITIES | 570 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| PAID WORK | SERVICES & GOVERNMENT | 1,539 | 2.7 | 3 | 4 | 4,200 | 4,410 | 6,309 |
| | PORT | 15 | 12.7 | 79 | 175 | 192 | 1,187 | 2,647 |
| | MANUF. & CONSTRUCTION | 334 | 1.7 | 24 | 0 | 577 | 8,170 | 0 |
| | ENERGY SECTOR | 4 | 14.7 | 2,879 | 0 | 60 | 11,772 | 0 |

*Figure 0-1 Simplified end-use matrix of energy carriers in relation to human activity*

*The example given in Figure 0-1 presents data referring only to two levels of analysis (the whole – at the level n - and its lower level functional compartments – at the level n-2) without describing functional and structural elements at lower levels. However, this multi-level analysis can be extended to lower levels by exploding the information referring to a given compartment – e.g. service government sector – into another end-use matrix focusing on the characteristics of the functional elements belonging to this compartment. An example of a lower level end-use matrix bridging the quantitative characterization across level n-2 (the Services and Government sector) and level n-3 (the functional elements of it is illustrated in*

Table 0-1).

Not only the energy end-use matrix represents an innovative analytical tool because of its ability of bridging quantitative information across different levels of analysis but it also makes it possible to avoid other limits of conventional quantitative analysis:* Moving away from the concept of energy efficiency of a city, toward the concept of energy performance of a city;

* Moving away from a mono-scale mono-dimensional quantitative analysis of efficiency toward a multi-scale multidimensional quantitative analysis of performance; * Moving away from predicative representations (deterministic results uncontested in relation to both definitions and assumptions) toward impredicative representations (contingent results depending on the choice of definitions and assumptions);

* Moving away from models providing representations chosen by the analysts, toward an approach generating representations chosen by the users of the analysis;

* Moving away from "dead quantitative assessments done once and for all", toward "living and flexible information spaces used for co-production of knowledge"

*Table 0-1 End-use Matrix (level n-2/n-3) describing the metabolic pattern of the Service and Government sector of Barcelona (excluding transport) against categories of human activity*

| | HA | US | EMR | | | EJP | EMD | | | EUSP | ET | | | VA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Elect. | Heat | Fuel | | Elect. | Heat | Fuel | | Elect. | Heat | Fuel | |
| | Mh | km² | kWh/h | MJ/h | MJ/h | €/h | kWh/m² | MJ/m² | MJ/m² | €/m² | GWh | TJ | TJ | M€ |
| **SERV. & GOV.** | **1,539** | **31.8** | **2.7** | **2.9** | **4** | **39** | **132** | **139** | **198** | **1,884** | **4,200** | **4,410** | **6,309** | **59,956** |
| Education | 101 | 3.6 | 1.3 | 6.3 | 0 | 35 | 38 | 177 | 0 | 986 | 135 | 637 | 0 | 3,542 |
| Healthcare | 157 | 1.9 | 1.4 | 1.3 | 0 | 22 | 116 | 104 | 0 | 1,805 | 223 | 201 | 0 | 3,477 |
| Offices | 641 | 7.0 | 1.9 | 1.2 | 0 | 45 | 177 | 112 | 0 | 4,075 | 1,246 | 792 | 0 | 28,697 |
| Commerce | 321 | 8.3 | 4.1 | 5.4 | 0 | 35 | 156 | 208 | 0 | 1,337 | 1,300 | 1,730 | 0 | 11,114 |
| Hotels, bars, etc. | 135 | 2.0 | 2.2 | 2.0 | 0 | 37 | 149 | 133 | 0 | 2,467 | 304 | 270 | 0 | 5,031 |
| Other | 119 | 3.7 | 5.9 | 3.0 | 0 | 33 | 190 | 99 | 0 | 1,063 | 696 | 360 | 0 | 3,881 |
| Transport | 65 | 5.3 | 4.6 | 6.5 | 104 | 65 | 56 | 80 | 1,199 | 800 | 296 | 419 | 6,309 | 4,212 |

**Potential developments based on the use of this tool**

(1) as done with the Covenant of the Mayors the approach presented in this deliverable can be used to develop a software used to represent the performance of cities shared on internet. The specific characteristics of the end-use matrix would make it possible for the administrators of the city to make the website interactive to sustain a permanent process of quality control of the information (using the same rationale of Wikipedia) to generate a more robust knowledge of the metabolic pattern based on benchmarks associated with specific end uses;

(2) the specific organization of data in the end-use matrix makes it possible to reach a shared agreement on a standardized characterization of the metabolic pattern of cities in relation to: (i) analytical tools - how to analyze and how to improve their energetic performance; and (ii) best practices - how to solve practical problems by studying the efficacy of specific functions in relation to final cause (contextualized problems) and of specific structural elements in relation to specific functions (technical problems); (iii) policies – how to assess the effectiveness of applied policies in relation to the expected results.

**Policy Recommendations**

In order to deal more effectively with the complex problems associated with sustainability it is time to abandon the logic of the Occam's razor – i.e. analytical tools should be as simple as possible – and embrace the philosophy of complexity – i.e. analytical tools should have a discriminatory power capable of identifying and characterizing all the relevant aspects for policy. This implies that an approach to quantification still based on the tools developed by Newton and static tables reflecting the pre-analytical choice of just a scale and dimension of analysis at the time should be considered as inadequate for supporting sustainability policy discussions in the third millennium. It is time to develop innovative forms of quantitative analysis that are:

i. capable of handling simultaneously multiple scales and multiple dimensions of analysis;
ii. transparent and capable of being co-produced in participatory processes.

## Tasks of this deliverable related to WP4

**Task 4.2. Internal view of energy systems**

The MuSIASEM can provide insights for an informed debate about the technical and economic factors determining the profile of consumption of energy carriers over the different sub-sectors of the socio-economic system, such as the service and government sector, the productive sectors and the household. This view will provide information on energy services (energy end uses) that are needed in order to guarantee the functions to be expressed by the dissipative compartments of the society and therefore give options of improvement in terms of energy efficiency.

**Task 4.3. Using the MuSIASEM as a decision-making tool for creating options in terms of feasibility, viability and desirability for energy systems**

This multi-scale integrated analysis can be used as a tool for assessment and decision-making in understanding how different forms of energy carriers are used to perform different societal tasks, and to look into the external constraints limiting the supply of the required energy inputs. These can thereafter be used to elaborate upon options of feasibility and biophysical viability as well as desirability to take action in terms of energy efficiency.

In D 4.3 we illustrate an application of the MuSIASEM in the form of an end-use matrix describing the metabolic characteristics of the different functional and structural components of a city (Barcelona is used as case study).

# 1 How robust and effective are narratives, targets and strategies for sustainable cities in EU?

(Lead author Raul Velasco-Fernández)

## 1.1 An analysis of the narratives and the formulation of objectives in the Covenant of Mayors

One of the most referenced agreement guiding energy policies by European cities is the Covenant of Mayors (CoM) (European Commission, 2008). The CoM is a voluntary commitment promoted by the European Commission that started in 2008 and it has been signed by more than 6800 cities in 57 countries. This initiative looks for a larger engagement of cities in the achievement of the 20-20-20 targets stablished in the climate energy package: *cutting greenhouse gas emissions by at least 20% of 1990 levels, cutting energy consumption by 20% of projected 2020 levels by improving energy efficiency and, increasing use of renewables (wind, solar biomass, etc.) to 20% of total energy production* (European Commission, 2015). The CoM recognizes local governments as key drivers for energy transition and for fighting against climate change at the level of governance closest to citizens. The signatory mayors declare their commitment towards working to achieve more decarbonized and resilient territories, and to cooperate in the context of the Global Covenant of Mayors by sharing their experiences.

However, even if the motivation is clear and shared, the definition of the strategies and the targets to validate policies are not. Multilateral policy agreements are usually based on high degrees of ambiguity when coming to the definition of specific targets and protocols of assessments. They are required to balance the diversity of interests in play in order to achieve a viable compromise for all parts. The more than 6,800 CoM signatory cities have a great variety of geographic, climatic and historic characteristics generating a high number of local political trade-offs and clashes of interests, making an unmanageable technical challenge to define a common set of targets, and heterogeneous socio-economic situations,. In the rest of this section we examine the problems faced when looking at the proposed targets and protocols of accounting.

### 1.1.1 The problematic use of generic objectives

A general objective is easy to define – e.g. “cutting greenhouse gas emissions” - but at the moment of defining a target – e.g. “cutting greenhouse gas emissions of 20% against the 1990 baseline year” we may face a situation in which it is almost impossible to identify protocols of accounting capable of calculating the chosen targets across the more than 6,800 cities included in the CoM.

There are practical problems – the unavailability of data for certain years – but also deeper epistemological problems – how to define the boundaries to be considered in relation to externalization? (Should we consider the embedded emissions in the goods and service consumed in the city and produced elsewhere?); What has changed and how in the considered period of time? Is the chosen method to account $CO_2$ equivalents (what should be included in the calculation of greenhouse effects?) shared by all the constituents of the different cities? Adopting a “one size fits all” choice of protocol of accounting can make it difficult and contested any assessment of the emissions in the first place.

Even worse is the policy challenge: how to translate into policy the chosen targets?

Unfortunately, when dealing with environmental agreements (see the discussion in Deliverable 4.1) it is rare to find discussions on the robustness of the analysis used to identify the criteria, indicators, targets or the expected consequences of these choices (see the discussion of these problems in Deliverable 4.1). This discussion is important because pre-analytical choices imply considering or neglecting different pieces of information. For example, in the CoM it has been decided not to include the accounting of $CO_2$ referring to the indirect emissions associated with the activities – carried out outside the borders of the city - needed to produce the goods consumed inside the city (e.g. food, construction material, durable goods). On the other hand, if we would decide to assess also indirect emissions, then the life style of residents, determining the profile of goods and services consumed in the city and the quantity and quality of infrastructures required to produce them would become a key information to inform policy. Therefore, when considering only the direct emissions of $CO_2$ associated with activities taking place inside the city we decide to consider only to the effects of the activities carried out inside the city ignoring the effect on activities carried out elsewhere. The choice of ignoring the embodied emissions will boost the selection of policies based on cost shifting strategies (externalization of the problem outside the borders of the city).

Another complication is determined by the special situation during the transition to an alternative energy matrix. In transitional periods new renewable infrastructures (wind mills, photovoltaic plants) and renewable technologies (electric cars and scooters) are still produced using fossil fuels (Smil, 2016). This implies that industrial cities that decide to produce alternative energy technologies inside their borders can be penalized by evaluations obtained using a protocol assessing only direct emissions. An increase in end-uses in: (i) the construction sector (consuming a lot of steel and cement) needed for the construction of green infrastructures; and (ii) the industrial sector consuming a lot of energy and energy intensive materialsneeded for the construction of an alternative energy matrix will increase the energy consumption and emissions of these cities, during the transition to alternative energy sources making them break the covenant.

Again we can see the importance to avoid the adoption of generic targets without being able to contextualize and articulate what exactly the targets want to achieve. What is needed to obtain this contextualization and articulation is a holistic approach capable of analyze in an integrated way the diversity of energy conversions required for: (i) using energy carriers to express the different end-uses in specific functional elements of the city; (ii) using primary energy sources to generate the energy carriers consumed in the city. In addition to this, the approach has to be able to track the geographic location of the energy transformations, in order to be able to make a distinction between the activities taking place inside and outside the borders of the city. Only using a richer characterization of how the structural and functional elements determining the metabolic pattern of the city use energy carriers it becomes possible to generate a more robust and effective definition of strategies and targets for policy.

In order to be able to choose, implement and monitor effective policies one should have available an exhaustive analysis of who is using, within the city, which type of energy carrier, how and why. More specifically one should be able to assess:

(i) the link between the various changes in the metabolic pattern of the city – which change in the mix of activities of the city is determined by a chosen policy - and the expected results (e.g. reduction in emissions, reduction in energy carrier consumption);
(ii) the effects of the changes determined by a chosen policy on the performance of the city in relation to other criteria not related to energy – i.e. quality of life, economic performance, ecological impact on the local ecosystems.

It should be noted that the complex relation between the results determined by the optimization of local reduction of energy uses and emissions and the overall performance of the city (i.e. the change of the set of functions expressed by the city) is further muddled by the openness of cities implying the externalization of the emissions associated with the production of goods consumed inside their borders.

### 1.1.2 The problematic assessment of emissions

Coming back to the CoM in relation to the targets on emissions (in Annex III) we find again a generic definition: "*quantification of the amount of greenhouse gases ($CO_2$ or $CO_2$ equivalent) emitted due to energy consumption in the territory of a Covenant of Mayors signatory during a specific year -it allows identifying the principal sources of emissions and their respective reduction potentials*". This sentence requires the definition of a specific protocol provided in Annex III that, as noted, is based on the pre-analytical decision of considering only gas emissions associated with activities inside the city, but not with the production of imported goods.

A guidebook: *How to develop a sustainable energy action plan (SEAP)* (European Commission, 2010) gives guidelines on how to operationalize the targets of CoM. When coming to the definition of sources and availability of data these guidelines are flexible in relation to the year: "*if the local authority does not have data to compile an inventory for 1990, then it should choose the closest subsequent year for which the most comprehensive and reliable data can be collected*". However, they do not indicate – in relation to the assessment of energy carrier consumption which type of data should be used – e.g. the categories of energy carriers, benchmarks to assess how are they used, the indication of who is using them, what is the end-use that requires their consumption. The same level of ambiguity is found in relation to the specification of the type of emission to be accounted "*we mainly refer to $CO_2$ in these guidelines, but it can be understood to mean also other GHGs like $CH_4$ and $N_2O$ in the case that the local authority includes them*". In fact, also in this case, the choice of data depends on the method selected for $CO_2$ calculation.

The two main methods suggested differ in relation to the pre-analytical choice of considering or not considering the emissions embodied in the energy inputs consumed in the city:

(i) Method 1 - calculation based on standard emission factors (from the IPCC) considering only the direct carbon contents of the fuels used inside the city *PLUS* the fossil fuels burned outside the city to produce energy carriers (electricity and process heat); or

(ii) Method 2 - calculation based on emissions factors following LCA principles. This method includes emissions taking place outside the territory that are associated with final fuels combusted inside (e.g. those ones generated in refining crude oils or cropping and harvesting when producing biofuels). We can notice again that the logic of LCA is not applied to the assessment of embedded emissions that refer to the production of other inputs (e.g. food) outside the border of the city.

The CoM guidebook explicitly points that "*the baseline $CO_2$ inventory will essentially be based on final energy consumption*" (end-uses associated with activities in the residential, transport, service sector) although "*also those other than energy-related source may be included in the BEI*" (without specific definitions). However, this is another pre-analytical choice affecting the final assessment. The rule of the protocol defining the value of the Baseline Emission Inventory (BEI) and the Monitoring Emission Inventory (MEI) excludes the accounting of the consumption of energy carriers used to develop and implement low emissions technologies (e.g. electric cars). Other emissions that should be excluded in the assessment are those of industries involved in the EU Emissions Trading System (even if this complicates the characterization of energy end uses), aviation, shipping, fugitive emissions from production, transformation and distribution of fuels, process emissions of industrial plants, use of products and fluorinated gases. Other emissions that are not be included are those of agriculture and the ones determined by land use change and forestry. Finally, there are other sectors that are only "recommended to be included" in the accounting if they are in the SEAP. They include industries not involved in EU ETS, highways and rail transportation out of local competence, local ferries, off-road transport, wastewater and solid waste treatment or fuel consumption for electricity production.

The exclusion of all these sectors reduces the quantity of energy on which to apply the generic target of 20% reduction. This means that the 20% or reduction will be just over the 70% of the total direct emissions (a reduction of just 14%). However, this reduction will be achieved only if, in the next years, the other sectors not included in the SEAP will do not increase their emissions.

Another degree of freedom in the implementation of CoM is given by the definition of target of reduction: "*The local authority can decide to set the overall $CO_2$ emission reduction target either as 'absolute reduction' or 'per capita reduction'*" (European Commission, 2010). A city can decrease its absolute emissions just by decreasing its population, or the number of tourists visiting even while increasing the per capita emissions or by changing its demographic structure with its associated consumption patterns. On the other hand, assessments per capita should neither be considered as good indicators, because energy uses and emissions refer to "activities" occurring inside the borders of the city and not to the activities of the residents. Cities are attractors of tourists and workers that commute every day contributing to the metabolism of the city, but that are not accounted as residents. As shown in our case study (Section 3.2.2), when characterizing: "which type of energy carriers is used, why, how and by whom" it is important to map biophysical flows of energy carriers onto hours of human activity taking place in the city referring to residents, commuters and tourists.

Finally, we want to flag again that an indicator based on just "reduction of emissions" is a poor indicator. As explained in Deliverable 4.1 if an economic crisis generates a reduction of the economic activity increasing the unemployment in the city, this will be considered as a successful reduction of emissions, even though this would certainly be an undesired way of achieving the results sought in the CoM. As discussed in section 1.2 (Fig. 1) of Deliverable 4.1 of EUFORIE, reviewed version (Giampietro, Sorman and Velasco-Fernández, 2017), this situation already happened during the economic crisis of 2008: The reduction in emissions due to the collapse of the EU economy was indeed considered as a success by the European Environmental Agency... A similar statement was posted in the website of *Diputació de Barcelona* regarding the same period 2005-2012: "*Energy consumption has dropped 5% in absolute terms and 11% per inhabitant. Similarly, emissions have fallen by 19% in absolute terms and 24% per inhabitant. It seems therefore that it is on the path marked by the Mayors' pact.*" (Diputació de Barcelona, 2018)

### 1.1.3 The problematic handling of quantitative energy assessments

The problems in the definition of targets and the ambiguities in the proposed accounting frame in CoM not only affect the usefulness of the information in relation to emissions. We find similar problems also when checking the other two objectives: (i) increasing the use of renewables to 20% of total energy production; and (ii) cutting energy consumption by 20% by improving energy efficiency. As discussed at length in Deliverable 4.1, there are qualitative differences that must be taken in account when generating quantitative assessments in energy metabolism. Quantitative analysis has to characterize the overall effect referring to the combination of two processes:

(i) how are Primary Energy Sources used to produce Energy Carriers; and
(ii) how are Energy Carriers used to produce End-Uses.

The quantitative analysis of these two processes should consider the qualitative difference between different energy forms – for example thermal energy carriers – e.g. heat and fuels - or mechanical energy carriers – electricity.

In fact, when looking at policies aimed at the increasing the use of renewable it is important to develop a quantitative analysis capable of identifying existing problems. At the moment the problem is not the "production" of electricity but it is how to synchronize the "production and consumption" of electricity. The current problem of integration of intermittent sources of electricity into existing grids nicely illustrates the implications of the fact that electricity is a form of mechanical energy. Mechanical energy refer to movement (in the case of electricity the movement of electrons in the cable), therefore we must produce electricity when is needed and we cannot inject electricity in the grid if nobody will consume it. At the moment lack of viable large-scale storage capable of taming their intermittent nature represent a serious limit to their expansion (Lindley, 2010).

This difference entails important implications for the accounting referring to targets used in policies dealing with alternative electric sources. In fact, we should consider at least three categories of kWh of electricity:

(i) baseload electricity – an electricity supply quite constant in time, associated with high values of utilization factors of the power capacity (1 MW of this type of power plant is used as much as possible);
(ii) peak electricity – an electricity supply which can be ramped-up when needed, associated with a low utilization factor of the power capacity (1 MW of this type of power plant is used only when needed but it is there when needed);
(iii) intermittent electricity – an electricity supply that may be there when is not needed and not being there when is needed, associated with a very low utilization factor (1 MW of this type of power plant is used only when both the supply and the demand of electricity coincide in time).

Therefore, when defining targets on expansion of renewable primary energy sources used for either producing electricity or heating we cannot compare or sum in general terms Megawatts (MW) of power capacity – in relation to the size of power plants. In fact, 1 MW of power capacity of a nuclear plant is generating as average electricity 80% of the hours in a year, whereas a MW of power capacity of a Photovoltaic plant depending on its location and the pattern of consumption of the grid can generate electricity 15-20% of the hours of a year. Measuring quantities of "MW" referring to different types of power plants does not provide useful information.

In the same way we have to be careful when comparing or summing MJ of energy carriers when they refer to different energy forms. In fact, exactly like not all the MW of power plants are equal, it is also true that not all the Joules of energy carriers are equal. For example, 1 MJ of electricity (that can also be measured in 0.278 kWh) has a different quality than 1 MJ of heat (that can also be measured in 0.278 kWh). We can use different units of measurement – e.g. 1 MJ = 0.278 kWh = 239 kcal – for the same quantity of a given form of energy, but we cannot sum MJ of electricity to MJ of fuels because these assessments refer to energy forms of different quality: electricity is a form of mechanical energy whereas heat is a form of thermal energy. Measuring quantities of "MegaJoules" (or "kWh") summing different types of energy sources does not provide useful information. More details on this point in Section 3.

The distinction over these three different types of electricity implies that for the moment a large scale introduction of intermittent renewables (aiming at a huge increase in the consumption of electricity) would require avoiding mismatches between the production and consumption of electricity. This can be obtained either by a strong political intervention aimed at generating a dramatic change in the patter of demand or huge investments in (and technical viability of) storage capacity. Changing the pattern of demand would require: (i) using smart meters to use the market for reducing the demand through the increase of prices. Bur a strategy based on price control implies the clear risk of reducing the quality of life of the poorest urban residents and the risk of increasing energy poverty; (ii) establishing price thresholds in relation to categories of end uses - e.g. using a selection of categories as proposed by Arrojo (2006) in relation to limiting water consumption in a new water culture. The approach is based on the definition of different categories of energy end-uses referring to different functions expressed in the city: energy-life (household), energy-citizenship (services), energy-business (industry), energy-food (agriculture). Dividing the total amount of consumption of electricity over different categories of end-uses it becomes easier to handle the problems generated by intermittency in the supply (identifying the pattern of demand of the different categories) and boost the efficacy of available storage capacity (identifying the storage capacity in the different categories).

Finally, there is another important consideration to be made, often missed in the standard framing of energy policies. We should expect that our societies and our cities will operate for a certain period of time (at least a couple of decades) in a transitional period in order to move from an energy matrix based on fossil and nuclear energy to an energy matrix based on alternative energy sources. In this transitional period, our societies and cities will have to decide how to combine gas power plants and renewables (Fickling, 2017) to match the characteristics of the supply and demand side.

To govern this transition it is essential to be able to know where the different energy carriers are used, how and why. The experience done with the *Energiewende* flags the risk that without differentiating between diverse forms of electricity a regulation based only on monetary variables may end up by pushing the partial use of baseload power plants (e.g. coal power plants) as peakers, causing a clear reduction in the performance of the electric sector in relation to emission reduction (Cembalest, 2016; Smil, 2017).

## 1.2 Conclusion

The brief discussion of the narratives, targets and strategies for sustainable cities found when looking at the Covenant of Mayors confirms the findings of Deliverable 4.1: the quantitative analysis of the energy performance of social-systems and sub-systems – e.g. cities – used right now to guide sustainability policies is based on a simplistic definition of "efficiency" and therefore it does not provide the information that would be required for an effective policy-making.

In particular:

(i) the concept of efficiency – i.e. that "targets" defined in generic terms (a reduction of "emissions") should be considered as good "by default" - is simplistic when used for guiding policies;

(ii) there are two different sets of relevant energy conversions: the production of energy carriers (Primary Energy Sources → Energy Carriers) and the consumption of energy carriers (Energy Carriers → End Uses) that require distinct accounting methods and models and thus indicators and targets;

(iii) the two non-equivalent characterizations of production and consumption of energy carriers have to be integrated across different scales of analysis to obtain an overall assessment of their effects on the whole metabolic pattern. This assessment must refer to different criteria of performance – e.g. emissions, increased use of renewable energy, reduction of consumption, reduction of economic costs, effects on the quality of life. An analysis of the performance across scales and with many criteria requires the generation of a complex information space;

(iv) the definition of boundaries, a pre-analytical step required to carry out quantitative analysis is tricky. Yet this decision will determine what should be calculated as "embodied" in the inputs imported by the city. Depending on the purpose of the analysis or the chosen protocol the definition of boundaries can change. The implications of this pre-analytical decision should be openly discussed with those that will use the result of the analysis to guide policy;

(v) the calculation of the emissions can be seen as a straightforward operation that can be done just by inserting a given set of data in a given protocol. However, the choice of a protocol rather than another has important "political" implications and does require a careful consideration. There are no protocols that can be applied - "one size fits all" - to different types of cities operating in different contexts and in relation to different indicators of performance. What should be included in the calculation of "emissions" is always arbitrary: there are $CO_2$ emissions, that are different from emissions of pollutants relevant for the quality of the air of the city, that are different from GHG emissions (including other gases beside $CO_2$ relevant for the atmosphere). Moreover, there are direct emissions, indirect emissions, embodied emissions in direct inputs and embodied emissions in indirect inputs...

When considering all these points and when looking at the proliferation of methods and sustainability goals to be monitored, the most effective strategy for generating sustainability indicators is to organize the process in phases. First, one has to generate a flexible integrated characterization of end-uses describing the energy metabolism as a set of functional and structural elements making up the city. This core of data has to cover all the relevant factors to be considered in a policy discussion.

This result can only be achieve through a participatory discussion of both the indicators to be used for the definition of targets and the methods of calculation of the data required for monitoring the situation.

In the rest of this deliverable we present such analytical tool providing a detailed definition of:

(i) the taxonomy of end-uses considered as relevant for policy, organized on different levels of analysis (the framework of relations over the constituent components of the city);

(ii) the type of energy carriers (electricity, heat, fuels) used in each one of the considered end-uses (what type of energy carriers are used);

(iii) how much energy carriers of each type is used in each end-use;

(iv) why the city is expressing the chosen end uses (identification of the functions to be expressed);

(v) the characteristics of the end use (how the energy carriers are used for expressing the given functions);

(vi) who is determining the set of functions expressed in the city.

# 2 Energy and climate change: the agenda of Barcelona

(Lead author Raul Velasco-Fernández)

## 2.1 The Energy, Climate Change and Atmospheric Quality Plan (PECQ)

Barcelona has been updating his energy policy agenda in the form of plans. The *Energy Improvement Plan* (PMEB) was implemented in the period 2001-2010 (Ajuntament de Barcelona, 2002) and now the *Energy, Climate Change and Atmospheric Quality Plan* (PECQ) is being implemented in the period 2011-2020 and in the framework of CoM (Ajuntament de Barcelona, 2011). These plans have the goal to minimize its environmental impact taking responsibility and committing to sustainability issues at the local and global level. The discussion in this chapter is going to be based on the PECQ, as it is the current plan.

PECQ follows the guidelines established in the previous energy program of Barcelona (PMEB). However, it has improved in relation to methodological aspects regarding the diagnosis of the issues to be addressed. PECQ addresses in details how to analyze specific aspects related to energy uses and the impacts derived by the consumption and production of energy carriers. It also addresses relevant issues such as: (i) the air quality and the dispersion of contaminants; (ii) ethnographic studies on the social behavior patterns toward energy consumption; (iii) a detailed characterization of some industries; (iv) an economic analysis of the city and the possible effects that PECQ policies may have on it; (v) a detailed analysis of the characteristics of the residential sector. The program was based on a wide participatory process involving social actors from different entities as: neighborhood and professional associations, trade unions, political parties, companies, guilds, universities, research centers and public administration. More than 250 people were involved and more than 900 proposals were collected. The results of this effort are presented in a report of almost 400 pages providing a wealth of valuable information in relation to the energy performance of Barcelona including: demographic evolution and population densities, stock of building by types and ages, labor structures, commuters and tourists' patterns, vehicle park profile, energy generation by source, technology and regime, electricity and gas network analysis or historic evolution of ITC technologies in households. We were able to generate the application of MuSIASEM presented in this deliverable using information from this report.

In these plans the choice of energy targets for the city of Barcelona considered simultaneously global issues such as climate change and local problems such as air quality, energy prices, resource limitations, but no mention to inequality of supply or energy poverty. To make things more difficult, as explicitly mentioned by the PECQ, these problems have to be handled while guaranteeing an adequate supply required to support the socio-economic activities of the city. This formulation of the problem flags the complexity of the required analysis. The description of performance and the controls implemented through policies must be effective in relation to: (i) different scales of analysis - one has to characterize the performance of the city in relation to international environmental issues (e.g. climate change) at the global scale and the performance of the city in relation to process that can only be observed at the local scale; and (ii) different dimensions of analysis – one has to consider simultaneously social, economic, technical and environmental issues.

In relation to this challenge PECQ is organized in two main programs addressing two different but interrelated issues: (1) the overall energy performance of the city, which is addressed in the city program, in general terms. That is, it contemplates actions related to the energy demand of the different sectors: households, transport, commerce, services or industry; (2) the performance of the energy transformation that directly depends on the city hall management, which is addressed in the municipal program. This program refers to decisions taken directly by the administrators of the city in relation to the performance of public buildings, street lighting, municipal fleet, urban services or a new renewable energy supply facility managed by the municipality (this program addresses specific targets of the CoM). According to the data found in PECQ (Ajuntament de Barcelona, 2011) – Fig. 194 and Tab. 78 - the city program tackles to around 97% of the final energy consumption of the city, but it receives 1% of the city investment on projects of PECQ, whereas the municipal program refers to around 3% of the final energy consumption in Barcelona, and it receives 99% of the total economic investment from the city hall (1,960.23 M€).

Getting back to the methodological discussions presented in Section 1, it should be noted that the quantitative assessments of final energy consumption found in the PECQ (the assessment of 3% vs 97% of the final energy consumption) can be misleading. The accounting method used in PECQ is based on a systemic summing of joules of energy carriers of different qualities - electricity, heat and fuels - without using conversion factors. As explained in detail in Section 3 this accounting should be avoided. In this specific example "the generic sum of quantities of energy carriers" of the Municipal consumption refers to a mix having a larger fraction of electricity (more buildings as end users) and a lower fraction of fuels than "the generic sum of quantities of energy carriers" of the overall consumption mix with many more cars as end users. Then if we would account the final energy consumption in PES equivalents as TOE, we may find (depending on how we decide to account for the difference in quality between J of electricity and J thermal) that the proportion of the municipal consumption would result higher (depending on the mix of PES used to produce the electricity and the conversion factors...). See (Giampietro and Sorman, 2012) for more details on this issue.

## 2.2 The challenge of integrating heterogeneous information across different levels and dimensions of analysis

Definitely the PECQ provides an outstanding amount of diagnostic information giving a very rich picture of the different aspects affecting the energy performance of the city. However, if we want to use only the wealth of heterogeneous information space in this 400 page report, it is impossible to find an integrative framework to generate a coherent simulation of possible futures.

Throughout the report one can find convincing and concrete explanations about relevant aspects to be considered to study the energy performance of the city. For example, when analyzing the electric consumption of Barcelona, we can find historical comparison regarding the overall consumption (7,536.66 GWh in 2009, 29% more than in 1999) and a decomposition of this overall value by sectors and years (the household change from 1,711.36 GWh in 1999 to 2,289.58 GWh in 2008). This makes it possible to see the quantitative relation between these data.

However, when relating this consumption with the population of Barcelona one can see the importance of discussing the pre-analytical choice leading to the definition of indicators. For example, when assessing the consumption of electricity per capita one can use the overall consumption in the city (which depends also on the activity of tourists or commuters that come to work every day in the city and not only on the activity of residents) and divide it by the population. Using this approach, one can see a growth from 3.87 MWh p.c. in 1999 to 4.66 MWh p.c. in 2008. In alternative one can only consider the electricity consumed in the residential sector. In this way one can measure a growth from 1.14 MWh p.c. in 1999 vs 1.42 MWh p.c. in 2008.

In this example, the use of two indicators provides types of information relevant for different purposes: the first indicator refers to the electricity that the city requires in average per habitant considering all the economic activities developed by residents, commuters, and tourists; the second refers to the electricity that the city requires for running the appliances in the houses. In relation to the first indicators the value can be affected by a significant increase or decrease in the number of tourists or residents. These two causes may not necessarily generate similar results. For example a reduction of the number of residents could not affect the economic performance of the city when compensated by an increase in the number of tourists, as in the case of Venice. In the same way, if we want to explain the reasons for changes in the second indicator – electric consumption inside the residential sector, the explanation given in the text of PECQ for Barcelona points at "*the massive introduction of ITC equipment (+11% of computers between 2004-2007) and microwaves (+24% between 2000-2005) in households would further increase the electricity demand on them* – which has been associated with a factor determining a reduction - *the improvement of efficiency in appliances would reduce its specific consumption over -23% and -37% between 1990 and 2006"*.

It should be noted that the relation over these two factors is not that simple and it would require additional information to be studied. For example, an increase in the number of computers per household may have the effect of reducing their utilization factor, their average power, their operation load. So changes in the electricity consumption per computer do not depend only on changes in technical efficiency. Another example of hidden reason for change can be represented by a change in the population of the city. According to the data found in the PECQ the population of Barcelona has decreased in the last decades from 1.9 million in 1979 (when the city used to have less buildings than now) to 1.6 million in 2008. This represents an important decrease of the density of population per area of building – i.e. a residential sector characterized by more square meters of residential space per person. Besides the number and quality of appliances we should also consider this as a factor affecting the energy performance of the households

Another example is given by a very good analysis of the effect of energy rehabilitation of homes in Barcelona (Agència d'Energia de Barcelona, 2011). In this report there is a matrix relating specific patterns of consumption of energy carriers (LPG, Natural gas, electricity, solar or gasoil) to specific pattern of end uses (heating, coaling, HSW - hot sanitary water - lighting or appliances) and to different ages and types of building construction. This kind of information is valuable for generating explanatory hypothesis and scenarios.

All these examples show that the selection of indicators used to explain changes in the level of consumption of energy carriers is a delicate but a possible choice. In order to get a useful perception of the pattern of energy use in the city it is essential to consider the typology of energy carriers (in the case of electricity even the hour at which we are consuming electricity can become relevant), who is using the energy carrier, to do what and how.

All these examples also show that if we want to characterize the performance of a complex system – like a city – and if we want to consider several relevant goals at the same time – e.g. global and local emissions, social, economic, technical, and environmental issues – the usefulness of our quantitative results depends on the pre-analytical choice of indicators that have to be integrated into a holistic picture. In fact, not only they have to provide all the relevant information, but also they must be integrated in a coherent description in order to make possible an informed deliberation over policy choices.

## 2.3 Reflection on the implementation of energy plan in Barcelona

### 2.3.1 The need of contextualization for best practices and policy advice

In the previous section we provided examples showing that a more articulated analysis of the factors determining different end uses of energy carriers is required in order to improve our understanding of the changes taking place in the different functional and structural elements of the city. In fact, the introduction of new end uses – i.e. new transformations of energy carriers expressing old functions or old transformation of energy carriers expressing new functions- will have the effect of increasing or decreasing the overall consumption of the city. Therefore, it is essential to gain a deeper insight in the factors determining the metabolic pattern of a city if we want to study and deliberate over the development of alternative strategies for improving the overall performance. In relation to this point *changing the pattern of behaviors* – i.e. moving beyond the traditional strategy of improving *technological efficiency* (= doing more of the same, but better) may represent an option much more effective both in terms of cost and timing than the option of technological innovation.

For example, by changing behaviors we can increase the utilization factors of technological objects, reducing in this way the requirement of technological equipment: i.e. sharing cars rather than producing more efficient cars. In the same way we can improve the efficacy of consumption by changing the behavior of the consumers, determining economies of scale: i.e. sharing chores or sharing infrastructures. Behavioral innovation, even more than technical innovation, can shake the business as usual routines and therefore challenge the status quo. For this reason, in a context of rapid changes it is normal to expect that powerful actors (the establishment) tend to preserve their dominant position by supporting the strategy of "more of the same but done better" (solving the problem of sustainability with technical innovation). However, not only behavioral innovation could solve problems quicker and at a lower cost, but also it can provide new opportunities in favor of social mobility.

As discussed earlier, the lack of integration in the analysis of the different factors driving the energy consumption of a city reduces the quality of the diagnoses used to inform policy makers. In particular this lack of integration makes it impossible to contextualize the insights (the narrative about causality) in order to get a more holistic vision of the performance of the city. Un-contextualized diagnosis of problems are often used to propose "*one size fits all*" solutions: that is list of "success stories" about solutions that are supposed to be repeated in different contexts and expected to generate the same results. Obviously reports compiling experiences from all around the world – e.g. *Cities, the new policy shapers in the energy transition* from Friends of Europe (2017) - are certainly useful because they show a variety of local initiatives that in different contexts have been effective in providing local solution. These initiatives include e-bikes in Belgium or financial mechanisms in Florida until the reuse of urine in local agriculture in Cameron. However, in order to be able to get full advantage of this wealth of potential solution it is essential to have a holistic framework making it possible to contextualize the solution and explains why this solution worked in that context but it is unlikely to work in a different context. Local changes in a metabolic pattern must result compatible with the "metabolic niche" generated by the rest of the metabolic network. Using rice straw for cooking is a well-established practice in rural China recycling biomass and reducing fossil energy consumption but it would be impractical in New York City. This is to say, that making lists of solutions that can reduce locally either the consumption of energy carriers or environmental impacts is certainly a useful activity. On the other hand it is also true that not necessarily the items in the list should be automatically considered as relevant policy action for fighting Climate Change and improve the performance of cities.

In relation to this point it is essential to address the complexity of the issue of sustainability and the fact that cities (open, adaptive and dissipative systems – see section 3) are very quick in adjust to changes imposed on them and move across hierarchical levels the effect of external constraints. A clear example of this is the Jevons paradox (Polimeni *et al.*, 2008). An improvement in energy efficiency at the local scale - e.g. a more efficient engine for cars - boosts the evolutionary drive of the making possible for the system (the car) to change into something else that consume more energy inputs – e.g. a more efficient engine translates into larger cars, with air conditioning, and a lot of additional gadgets.

For this reason it is important that when developing plans or developing international initiatives as the CoM the information space used to guide action and generate targets and indicators is a "living" information space open to adjustments and feed-backs. In particular the analytical framework must provide an effective understanding of the quantitative interrelation between processes observed and described at different scales using different dimensions. If this condition is not fulfilled, then there is the risk that commitments based on a "dead" information space not evolving in time and supposed to provide "one size fits all" solution will not be effective for achieving the desired goals. Moreover, as discussed in Section 1 the adoption of generic indicators that are not tailored on the specific characteristics of individual cities makes impossible for the local actors to have a proper evaluation of the results of their policy.

### 2.3.2 Ignoring that sustainability issues are political issues may lead to a poor quality of scientific analysis

Last but certainly not least there is an unavoidable political dimension in all discussions related to sustainability. In the brief discussion over the difference between technological innovation and behavioral innovation we mentioned that the very framing of the issue of sustainability has deep political implications. Policies aimed at technological innovation end up just subsidizing and promoting innovation carried out by private companies encouraging the consumption of the new products on the basis of perceived obsolescence and a social distinction (Veblen, 1899; Bourdieu, 1984). This imperative of innovation for "saving the planet" can be seen as a kind of greenwashing of the consumer society. In the case of global cities, they compete for appearing greener, more open and smarter than the others in order to attract more international investments, yuppies and rich tourists that would gentrify their central neighborhoods evicting the poorest part of the population. In this way, public institutions promote a Schumpeterian creative destruction in the name of sustainability, while ordinary people wonder why is cheaper and greener to buy a more efficient appliance than repairing their old one, why the house of a single rich person is labeled more environmentally friendly because of a lot of expensive green gadgets, than their small old apartments giving household to 6 persons. Reflecting on these examples one can only wonder whether is it possible to solve a problem by doing "more of the same" of the strategy that created it. If we accept this reflection, it is clear that we should reconsider both the narratives and the diagnostic tools that we are using when trying to fix sustainability problems.

The pressure of the establishment for going for a technical solution (doing more of the same but better) rather than a political solution (doing something else) is reflected in the systemic choice of local definition of efficiency (un-contextualized definition of indicators and targets) rather than a holistic deliberation on the definition of performance. Because of this pressure, energy policies are a mix of innovation grants and regulations focused on targets that are easy to measure: local efficiencies. This phenomenon – for which Elgert proposed the term *mesurementality* (Elgert, 2018) – is a spontaneous event. Rayner (2012) has put forward an explanation for the phenomenon of poor quality control of the scientific information used to guide policy under the name of "socially constructed ignorance". He argues that this phenomenon is not the result of a conspiracy but rather of the sense-making processes employed by individuals and institutions: "*To make sense of the complexity of the world so that they can act, individuals and institutions need to develop simplified, self-consistent versions of that world. The process of doing so means that much of what is known about the world needs to be excluded from those versions, and in particular that knowledge which is in tension or outright contradiction with those versions must be expunged. […] But how do we deal with […] dysfunctional cases of uncomfortable knowledge […]*?" (Rayner, 2012). A systematic elimination of uncomfortable knowledge, generalized and institutionalized throughout the system, can eventually produce a situation of 'ancien régime', that is, "*a state of affairs in which the ruling elites become unable to cope with stressors and adopt instead a strategy of denial, refusing to process either internal or external signals, including those of danger*" (Funtowicz and Ravetz, 1994).

*Measurementality* reduces political issues to technical issues, after defining numerical targets to be achieved, forgetting that definition of these numerical targets would require a deep and participatory political deliberation. Numbers are just another type of stories and their use in the "evidence based policy" paradigm (Saltelli and Giampietro, 2017) could hide the need of addressing the political issues associated with their choice.

For example in PECQ (a 400 page energy report) there is no mention to energy poverty, the social implications of power cuts, whereas in the last energy policy document from the city hall of Barcelona this is a is a crucial problem to be addressed (Ajuntament de Barcelona, 2016a). The technical aspects and the political aspects seem to be kept separated. Another missing issue in PECQ is the gender issues, that has been flagged as relevant by other reports – e.g. from Engineering Without Borders (Gonzalez Pijuan, 2018) – indicating a clear relation between energy poverty and gender.

These examples show that if we want to use an information space –e.g. the quantitative analysis of the performance of the city of Barcelona – to guide action, then the choice of narratives, indicators and targets is inextricably mixed with normative and political decisions. Therefore, an information space associated with the production of quantitative analysis that will be used to given normative indications for policy must be open, transparent and above all co-produced with the social actors that will be affected by the decisions made. Only in this way a diagnostic tool to be used to characterize the performance of the city will result useful in generating a shared understanding of the complex issues that modern societies and modern cities have to confront. Policy making requires an adequate supply of relevant information capable of providing anticipation in relation to all types of problems (economic, ecological, social, political). To guarantee the quality of this supply of information it is essential to guarantee an open process of co-production in which public institutions, the other actors, and scientists of different disciplines can deliberate in an open space what are the insights, the perceptions and the representations that have to be integrated in the quantitative analysis. The tool presented here may represent a step in this direction.

# 3 An application of relational system analysis to the metabolic pattern of energy in Barcelona

(Lead author Mario Giampietro)

## 3.1 How to generate a quantitative description of a complex metabolic system driven by human agency across scales and dimensions: the example of a city

### 3.1.1 Using the rationale of non-equilibrium thermodynamics to study the sustainability of cities

Wolman in 1965 talks of the metabolism of cities, without making references to concepts of non-equilibrium thermodynamics. Yet he perfectly identifies and describes the metabolism of a society in relation to this inside/outside interface:

> *"The metabolic requirements of a city can be defined as all the materials and commodities needed to sustain the city's inhabitants at home, at work and at play. Over a period of time these requirements include even the construction materials needed to build and rebuild the city itself. The metabolic cycle is not completed until the wastes and residues of daily life have been removed and disposed of with a minimum of nuisance and hazard".*
>
> (Wolman, 1965, p. 156)

In his analysis of New York City Wolman (1965) identifies input flows (coal, oil, natural gas, food) and waste flows (sewage, solid waste, air pollutants) – actually he proposes a sort of "end-use" matrix (but without generating a sudoku effect on the values across levels) - and also he suggests an "environmental pressure matrix" by comparing the requirement of inputs (e.g. water consumed by NYC) against the ecological funds used to get them – e.g. the rivers available in the area.

As explained more in detail below, non-equilibrium thermodynamics explains the possibility of stabilizing the identity of a dissipative system (be a tornado or a city) in relation to the fulfillment of two conditions:

(i) internal viability – the system must be able to express a set of transformations capable of reproducing its own structural and functional elements. This means that - given the assumption that the system has access to the required quantity and quality of inputs and the possibility of discarding the resulting quantity and quality of wastes – it is actually capable of metabolizing the required inputs (while dumping the wastes) to maintain and reproduce its functional and structural organization;

(ii) external feasibility – the process of self-organization of a system must take place in an admissible environment (favorable boundary conditions). This means that given the assumption that the system is maintaining and reproducing its functional and structural organization then the required inputs are available. That is, the system does operate in a situation in which the inputs are indeed available and the resulting wastes can be dumped somewhere else.

In relation to this point the concept of metabolism is particularly useful for framing this analysis because it implies studying two distinct sets of coupled processes taking place simultaneously, but that can be observed only adopting at two different scales:

(i) inside the black box – i.e. the metabolic processes taking place inside an organism or inside a city; and
(ii) outside the black box – i.e. the processes outside the control of the system that make it possible the interaction of the whole metabolic system with its context when gathering the required inputs and dumping the resulting wastes.

The idea of using the rationale of non-equilibrium thermodynamics to study the evolutionary drivers and sustainability of cities derives from the original work of Prigogine (Prigogine and Stengers, 1984). Since then it has been used for conceptual investigations about the nature of cities (Dyke, 1988b, 1988a; Allen, 1997; Von Schilling and Straussfogel, 2008). In particular, the openness of cities and their dependence on the activities of processes taking place outside their border has been described using the jargon of non-equilibrium thermodynamics using the concept of "entropy debt" (Dyke, 1988b; Von Schilling and Straussfogel, 2008; Pelorosso, Gobattoni and Leone, 2017).

> *"They maintain their internal order by utilizing an ambient energy flux and dissipating degrade forms of that energy into the environment. Internally, their order is maintained (or even increased), which occasions an "**entropy debt**" that is paid by the increased disorder of the environment".*
>
> (Dyke, 1988b, p. 114)

To better understand the concept of "entropy debt" we can get back to the basis conceptualization of the stability of dissipative systems in non-equilibrium thermodynamics.

The concept of **dissipative systems** was introduced in the field of non-equilibrium thermodynamics by the work of the Prigogine school (Prigogine, 1961, 1978; Glansdorff and Prigogine, 1971; Prigogine and Nicolis, 1977; Prigogine and Stengers, 1984). This concept represents a radical departure from the type of systems studied within the mechanistic epistemology of reductionism (Giampietro, Mayumi and Sorman, 2013). In fact, dissipative systems are: (i) thermodynamically open systems – so it is very difficult to define an uncontested border for them – they are made of what they metabolize, but they are different from their inputs…; (ii) they are operating far from thermodynamic equilibrium but still they can express a predictable identity in time because they can express a dynamic pattern associated with a quasi-steady state situation; (iii) they are fully dependent on the favorable gradients provided by their boundary conditions, but their own existence implies destroying these favorable gradients. For this reason they have to learn how to become something else in the long run. To make things more challenging is not event easy to observe a dissipative system, in fact we can only observe dissipative structures that are only a part of the whole.

A **dissipative structure** is the observable aspect of a dissipative system associated with the establishment of a dynamical régime that can be considered as a "reproducible steady state" – e.g. a tornado, a city. Complex adaptive dissipative systems use information for controlling and reproducing the expression of their dissipative structures (Giampietro, 2018). As illustrated in the example of metabolism of New York City given by Wolman, the reproduction of dissipative structures (what we see when we watch a city) depends on the possibility of reproducing the whole dissipative system generating the metabolized inputs and absorbing the generated wastes. Therefore a dissipative system, different from a dissipative structure, can be defined as a set of relations between: (i) what is happening inside the system (the city) – the pattern of dissipation expressing the structure; and (ii) the interaction that the system (the city) has with its context, based on processes keeping stable the boundary conditions. The original conceptualization given in non-equilibrium thermodynamics illustrates this set of relations quite easily.

> *"Let $dS_i$ be the entropy production in the system due to irresversible processes and $dS_e$ be the entropy flux due to exchanges between the system and the environment. The total entropy change of the system is given by:*
>
> $$dS = dS_e + dS_i \qquad [1]$$
>
> *The second law states that $dS_i > 0$. However, **if sufficient low entropy flux enters the system** – when $dSe \leq 0$ and it is possible that $|dS_e| > |dS_i|$ which implies that $dS < 0$. If this is the case then the system will be driven away from equilibrium. It is also possible for the system to eventually reach a steady state ($dS = 0$). It is the process which leads to this steady state and the accompanying coherent behavior which Prigogine, for special cases, has developed a theory for."*
>
> *(James Kay personal home page [https://www.jameskay.ca/musings/mep.pdf])*

Relation [1] can be used to describe the standard situation in which metabolic systems – such a living system or a city – operate. They can express a series of expected functions needed to reproduce the existing set of structural elements only if operating at a value of $\boldsymbol{dS \leq 0}$. The dissipative pattern expressed by the city or by its individual elements ($dS_i$) represents an "entropy debt". This implies that the city must be capable of importing a continuous flux of both energy and material inputs coming from the environment that represent the low entropy flux **– $dS_e$**. These material and energy inputs are those metabolized by the structural and functional elements operating inside the systems to stabilize the structure (the processes determining the value of **$dS_i$**). The concept of "entropy debts" proposed by Dyke indicates that the activities expressed in the city (the functions needed to reproduce structural elements) can be associated with positive quantities of **$dS_i$** that characterize in quantitative terms the amount of supply and sink capacity associated with the definition of **– $dS_e$** (the required inputs coming from outside the city and the emissions and wastes dumped outside the city or exported outside the borders) to compensate the original dissipation of flows.

Recalling the narrative of non-equilibrium thermodynamics is important because it supports our claim that the analysis of the sustainability of metabolic systems must be based on two non-equivalent descriptions of the system: an inside view - the processes generating the internal production of positive entropy - and an outside view - the processes compensating this positive flux of positive entropy with a negative flux. In turn the choices of quantifications in these different descriptions of the system must reflect the co-existence of logically independent framings:

*1. looking for factors determining the process of internal generation of entropy (dSi)*

This would be the end-use matrix describing the characteristics and the relations of the internal structural and functional elements needed to coordinate the different activities in order to express the emergent property of the whole. The second principle of thermodynamics tells us that each additional structural and functional component will require additional inputs for its functioning. That is we have to associate a processor of required inputs to both: (i) the ability of expressing functions; and (ii) the operation of structural elements.

As explained by Dyke:

> *"If human institutions and systems are dissipative structures we have to identify structures and relate their ability to sustain maintain and reproduce themselves within the limits of the resources (material and energy) available for them.(…). But each increment of interdependence requires new devices for establishing the internal coherence of the larger system.* ***And each new device has its cost, it "entropy debt"****.*

(Dyke, 1988b, p. 117)

The set of processes **capable** of expressing this *dSi* is described by the end-use matrix.

*2. looking for factors determining external generation of negative entropy flux (-dSe)*

In this case we are dealing with the need of characterizing the requirement of: (i) supply capacity of inputs; and (ii) sink capacity of wastes and pollutants – that a city must have in order to be able to express its functions through the set of transformations described by the end-use matrix. It should be noted that these factors refer to processes that are either outside human control (taking place in the biosphere) or are under human control but outside the border of the city (externalized through imports). This means that when dealing with the metabolism of cities beside the assessment of the required processes (internal activity in the end-use matrix) we have to consider also the processes required to guarantee admissible "boundary conditions". In the jargon of non-equilibrium thermodynamics the availability of the inputs needed to repay the "entropy debts" accumulated by the various processors operating inside the city. This second assessment is more difficult to achieve and can be done in different ways, depending on the assumptions used for the calculations (this is discussed below).

In fact, we have to calculate an *environmental pressure matrix* by looking: (i) on the supply side at the amount of primary sources (for energy, food, water, and mineral) that are required to guarantee the end uses of the city; and (ii) on the sink side at the amount of "primary sources" of sink capacity (the activity of ecological processes) that are required to absorb the resulting wastes and pollutants. At this point one has to decide what has to be included (or excluded) from the accounting depending on the purpose of the analysis. It is at this point that different logics can be adopted resulting in a proliferation of possible assessments.

It should be noted that this "entropy debt" is only paid **in minimal part** by the natural processes taking place inside the city (local environmental pressure). A large part of the entropy debt of cities is externalized to other social-ecological system in the form of "virtual quantities" of primary sources embodied in the input imported by the city. For example, it is well known that the agricultural sector – i.e. rural areas – consumes a large fraction of the total water consumed by a country (up to 80%). However, in developed countries this water, officially used in rural areas, goes in the production of food that is consumed almost entirely by urban dwellers. Even if nobody assesses the consumption of water in agriculture as a consumption of the cities (because the structural elements using this water – i.e. crop fields – are located in rural areas), in functional terms this water is used to produced food needed to feed the urban population and should be considered as a requirement of the city. It should be noted that this indirect consumption of water is orders of magnitude higher than the direct amounts accounted in city statistics.

As discussed in Section 1, when coming to the problem of how to assess the embodied quantities of inputs (or emissions) associated with the activities of a city, it is impossible to have a unique and uncontested solution. For this reason, in this deliverable, we suggest to keep separated the analysis of:

(i) the end-use matrix – focusing on the internal processes consuming energy carriers to express the metabolic pattern inside the city (the production of dSi). The end-use matrix identifies and characterize the pattern of use of energy carriers generating the entropy debt, and for this reason it generates information very relevant for policy;
(ii) the local environmental pressure generated by the city – focusing on the consequences on the local environment determined by the expression of end-uses inside the borders of the city;
(iii) the implication of the metabolic process of the city on other social-ecological systems – focusing on the level of "externalization" of its metabolic pattern (the openness to imports of the city). This pressure can be seen as a transfer of the repayment of the entropy debt (–dSe) to other ecosystems and other socio-economic systems.

The first type of analysis is needed to understand how the identity of the city – i.e. its peculiar characteristics, its technology, its economy, its lifestyles – is associated with a given end-use matrix – the overall requirement of carriers and the overall production of wastes and pollutions. The analytical tool proposed here – the end use matrix – presented in the following section - can be used to study the nature of the entropic debt.

In order to analyze the entropic debt, one has to assess first of all: (i) how much of this entropic debt is re-paid using natural processes and resources available *inside the borders of the city* – i.e. the local environmental pressure of the city; (ii) how much of this entropic debt is re-paid by *externalizing it to other social-ecological systems*.

In order to structure this analysis, we have first to:

1. track the various processes used to supply the city with the required flow of inputs – what are the Primary Energy Sources?, Primary Food Sources?, Primary Water Sources?, Primary Mineral Sources used by the city?
2. track the various types of sinks required to absorb the flow of outputs/wastes – what are the Primary Sinks for solid, liquid and gaseous emissions?
3. identify in geographic terms the location of the primary sources: Is the production of Energy, Food and Water carriers taking place within the border of the city?
4. Measure the level of openness of the city (what fraction of the goods and services consumed inside the city is produced inside the city, what fraction of the wastes is handled inside the city). How dependent if the city on imports from the outside and how much is the city externalizing its wastes/emissions?

After having gathered all the required pieces of information we can finally generate an integrated assessment of the performance of the metabolic pattern in relation to different criteria:

(i) quality of life in the city;

(ii) local environmental impact and quality of the local environment;

(iii) pace of depletion of non-renewable sources (dependence on non-renewable energy),

(iv) impact on the global atmosphere (GHG emissions);

(v) externalization of economic activities to other social-ecological system impacting other societies (ethical aspects of importing some types of goods or exporting some types of wastes);

(vi) externalization of economic activities to other social-ecological system impacting other ecosystems (ethical aspects of importing some types of goods or exporting some types of wastes);

In our view, if we want to use quantitative analysis for dealing with these different sustainability criteria, it is not possible to adopt a single quantitative representation based on a unique choice of metrics. For this reason, it is essential to organize the analysis of the metabolism of society in an integrated set of analytical tools to avoid an overflow of information impossible to handle. In relation to this point the conceptual framework of non-equilibrium thermodynamic is very useful in clarifying the different types of processes that should be considered to check the sustainability of the metabolic process.

In conclusion, when using the framework of non-equilibrium thermodynamics, we can identify three theoretical terms that can be used to describe the expected set of relations associated with the feasibility and viability of a metabolic pattern (Giampietro, Mayumi and Sorman, 2012):

$$dS_{MS} = dSi - dSe \qquad [2]$$

***dSi is about viability*** - the ability of the structural and functional elements operating in the system of expressing an integrated pattern of internal entropy production associated with the maintenance and reproduction of city identity. This term refers to the internal ability to generate the emergent behavior of the whole. In relation to this term the two examples of end-use matrix presented in section 3.2.3 (Figure 3-11 and Figure 3-12) represent an analytical tool aimed at organizing the quantification of the set of relations that have to be established inside the functional and structural elements of a city to express the expected metabolic pattern (assuming that the required inputs are available);

***"– dSe" is about feasibility*** – the availability of the required amount of "negative entropy" capable of maintain the expected favorable boundary conditions of the local processes of dissipation taking place inside the system. An "admissible environment" has to pay the "entropy debts" that the operations of the various processors used to express an integrated metabolic pattern are generating inside the system. This means that on: (i) the supply side – processes taking place in the environment must be capable of stabilizing the flow of required inputs; and (ii) the sink side – processes taking place in the environment must be capable of stabilizing the process of removal of wastes and neutralization of pollutants.

When trying to operationalize the quantitative analysis of this “entropy debt” in relation to the energy metabolism of a city we have to explore the interface between: (i) the internal metabolic pattern of energy carriers – what type of energy carriers, how much of each type are required, when and where; (ii) the characteristics of the energy sector generating the required supply.

Finally, because of the very high level of openness of a city the concept of “admissible environment” no longer refers only to the boundary conditions determined by the natural processes taking place in the ecosystems embedding the city. When dealing with modern economies and especially when dealing with cities operating in developed economies the definition of an “admissible environment” refer to the possibility of importing from outside the required inputs and exporting unwanted wastes. That is, the economic process and trade make it possible to “externalize” different types of “entropy debts” to other social-ecological systems. In relation to this point the level of openness and its implications have to be addressed by tracking the inputs and outputs considering the implications that this externalization can have.

***$dS_{MS}$ is about the sustainability of the “emergent property” – the becoming identity of the city*** – when reaching a dynamic balance between ***+dSi*** and ***–dSe*** the metabolic system – in our case a city – can stabilize its metabolic pattern and adapt it to new circumstances and new aspirations. This means that through its evolutionary path a city has to remain capable of expressing a set of expected functions by reproducing and maintaining its structural elements. In the case of availability of surpluses of –dSe (the city is getting richer) these surpluses can be used to “improve” - depending on the normative narratives used to define it - the metabolic pattern by changing the set of functions (adding new ones or expanding the existing ones) and “improving” the efficacy of structural elements – i.e. producing “better” structural elements according to the selected normative narratives. In relation to this point, it is impossible to quantify in a deterministic way the perceptions of the constituent components living inside the cities (the people expressing their activities in it) about the desirability of the identity of the city. Assessments about desirability will always have a value-based bias and be contested. Obviously, constituent components – i.e. people expressing their human activity within the given metabolic pattern of the city – are endorsing the desirability of it by their actions: continuing to live, work or visit the city. Without achieving a minimum level of “desirability” the city would become soon a ghost-town – e.g. Detroit.

### 3.1.2 Using the concept of holons to analyze the relation between material and immaterial elements in complex metabolic systems

In the last decades a few heterodox scientific fields have developed useful concepts making it possible to better understand the functioning of complex adaptive systems, such as societies and cities.

Therefore, before moving to the detailed illustration of the application of relational analysis to the metabolic pattern of a city (in Section 4), we have to introduce another theoretical concept which makes it possible to handle the ambiguous relation between notional/functional (immaterial) and structural (material) elements of a metabolic system.

When dealing with the analysis of complex adaptive systems we have to admit that there are relevant aspects of the systems **that are not material: "***A human activity system can be defined as 'notional system' (i.e. not existing in any tangible form) where human beings are undertaking some activities that achieve some purpose*" (Patching, 1990). This fact implies that a system of accounting willing to reflect the complexity of a metabolic system has to take into account the existence of functional meanings that are "entailed" in the identity of the system, but that are not observable as material objects.

In his famous book "*The ghost in the machine*" Koestler (1968) illustrates the fact that there is always an immaterial component in organized systems that is associated to the meanings that the parts of the machine get in the notional system. The meaning - the final cause of the part operating within the machine - is associated with the functions they express when looking at the physical process aimed at performing an expected task. The function is associated with the meaning of the parts in relation to the whole. This logical bifurcation between two different types of representations is a source of epistemological problems:

(i) in the notional systems – the representation refers to the meaning of the functions; and
(ii) in the physical system - the representation refers to the observable structural organization of the parts.

When dealing with the analysis of complex adaptive systems this bifurcation implies a systemic degeneracy of the mapping between structural and functional types (Giampietro, Allen and Mayumi, 2006). A person (*a structural type*) can be a father, a professor, a violinist or a consumer (different *functional types*). In the same way a social role such as being a professor (*a functional type*) can be expressed by different typologies of persons – a woman, a man, an old, young, tall, short, person etc. (*structural types*). Koestler (Koestler, 1968, 1969, 1978) proposed the concept of holon to tame the systemic ambiguity faced when referring to specific couplings of structural and functional types. The term holon is an integration of two words: (i) the whole (the "HOL" part of the term) wants to make reference to the concept of holism – the function expressed in its context when the holon is considered as a whole; and (ii) the part (the "ON" part of the term) wants to make reference to the concept of particle, as in electron – the structural component when the holon is observed in its structural parts. The basic message of the term holon is that when studying the organizational structure of complex metabolic systems we cannot keep separated the analysis of the material and immaterial components. A holon is always a part operating in a context from which it takes its meaning and it is the context of its lower level components to which it gives meaning. The hierarchical organization of complex systems made of holon is called a "holarchy". When studying holarchies we have to learn how to establish relations between the structural and functional elements across the different levels of organization.

In the field of hierarchy theory (Simon, 1962; Whyte, Wilson and Wilson, 1969; Pattee, 1973; Allen and Starr, 1982; Salthe, 1985; Ahl and Allen, 1996) the concept of holon is described as an epistemic devices capable of handling the fuzzy mapping across different hierarchical levels of analysis: (i) a structural type (e.g. a person) is defined over three continuous hierarchical levels of analysis – i.e. *level n-2* tissues and cells/*level n-1* organs/*level n* the whole person; and (ii) a functional type (e.g. a professor) is defined over three continuous hierarchical levels – i.e. *level n* individual person/*level n+1* educational system/*level n+2* the society in which education takes place). In this complex representation the two types (structural and functional) do have a level of analysis in common – i.e. *at the level n* when observing the holon we see ***both a professor and a person***. However, if we want to carry out a quantitative analysis of the characteristics of the structural type - i.e. what type of professors (e.g. disciplinary knowledge, qualifications, teaching records) and attributes *at the level n+1* – we have to use data non-relevant for describing the characteristics of the physical body (e.g. sex, age, weight, medical records) *at the level n-1* .

In conclusion: (i) "non-materiality" can be associated with the concept of "functional" elements determined by relevant aspects of processes required to express specific behaviors of a complex system; (ii) "materiality" can be associated with the concept of "structural" elements determined by the given physical organization of its material parts. By adopting a metabolic approach, studying networks of energy transformations, we can measure the characteristics of both elements – non-material and material. The approach proposed in this deliverable is based on *relational system analysis* (presented below) used to design a conceptual framework useful for handling the ambiguity faced when analyzing functional and structural elements operating within a complex metabolic system – a city - across scales.

### 3.1.3 Using basic concepts of "relational system analysis"

Let's start from the definition of relational theory of systems provided by Rosen:

> *“any system is organized to the extent that it can be analyzed into or built out of constituent components. The characteristic relationships between such constituent components, and between the components and the system as a whole, comprise a new and different approach to science itself, which we may call the relational theory of systems”*
>
> (Rosen, 1991, p. 117)

Within this framework it is important to provide a definition of the term “system” in relational system analysis when dealing with social-ecological system.

> *“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).”*

This definition resonates with the definition of notional system given by Patching (1990) already quoted in the previous section.

> *“A human activity system can be defined as 'notional system’ (i.e. not existing in any tangible form) where human beings are undertaking some activities that achieve some purpose.”*

A constituent component is an essential part of the system, whose structural elements have to be reproduced, because it expresses functions needed to maintain the stability of the whole system.

Relational analysis implements the concept of notional system by identifying the existence of a hierarchy of final goals associated with the role and reproduction of “*constituent components*”, which in turn cooperate in order to express the emergent property making possible their own reproduction. That it, the goal of the reproduction of the city (final goal of the whole) has to be translated into the goal of the reproduction of the constituent components of the city (sub-level final goals). Then this definition of the identity of the components (in relation to the whole) defines in cascade other final goals across the various levels of the holarchy (the organized pattern of holons across hierarchical level) – (Koestler, 1968; Allen and Starr, 1982).

The integration across hierarchical levels of organization of the different semantic definitions of: (i) final cause – the purpose of the holon; (ii) efficient cause – the function of the holon; (iii) formal cause – the structural elements of the holon; and (iv) material cause - the admissible environment providing inputs to and absorbing undesired outputs from the holons - represent a powerful heuristic approach to the study of the complex nature of living and human systems. It makes it possible to identify inside the whole system (Barcelona) what are the constituent components (residents, commuters, tourists), why they do what they do (the final causes - what justifies their activity in

Barcelona), how they do what they do (the efficient causes – the various functions expressed by the people in Barcelona: the combination of human activity, technology and infrastructures, and consumption of energy carriers to express functions), what they use for expressing their function (the formal causes – describing the technology and infrastructures used to support human activity in Barcelona such a buses, trams, cars, hospitals) and what are the material conditions required for having the process of self-organization (the material causes - the set of inputs and outputs required at the local level such as gasoline, electricity, paved road). This indeed is the analysis based on the end use matrix that will be presented below. The definition of the mechanism of reproduction of the constituent components in terms of final, efficient and formal cause describes in detail the process of generation of the dissipative structure (dSi) – the entropy debt associated with the functioning of the city. This entropy debt has to be compensated by the availability of supply and sink capacity provided by its context. The analysis of external constraints and environmental impact requires the use of descriptions based on the material cause, reflecting the load that the dissipative structure is posing on its context.

The final cause of an adaptive, self-reproducing and self-maintaining system is the "emergent property" of the system: the ability to preserve and adapt its identity in time depending on internal changes in values or external biophysical constraints. This "emergent property" of the whole is what makes "the parts" meaningful and the whole more than the sum of its parts. This "emergent property" can be associated with the special identity making it possible to identify "the system" as something distinct from its environment in the first place. In the case of a city, we can say that a city ***must be capable of maintaining and reproducing its constituent components. In turn this requires reproducing the patterns of human activity expressed each year within its borders (in its built environment)***. In this way, we can identify the various functions expressed by the constituent components and study the structural elements used for expressing them.

In relation to the notional definition of an identity Giampietro et al. (Giampietro, Allen and Mayumi, 2006) say:

> *"The etymology of the term identity comes from Latin* identidem*, which is a contraction of* idem *and* idem*, literally ''same and same''. Therefore, the very concept of identity has to do with a mapping: ''the observed'' must map onto something used as an expected ''reference type''. An identity implies using a given name (label) which must be associated with two tasks performed simultaneously:*
>
> 1. *To define mental images useful for recognizing objects of interest. Those images consist of expected relationships between attributes of types used to represent the organizational structure of members that belong to an equivalence class.*

> 2. *To identify physical entities perceived as legitimate members of that equivalence class. Individual realizations of the relative equivalence class must express the expected pattern so as to be recognizable when the mental image is used in a comparison."*

In this definition we find three factors in play: (i) the notional definition of the system (associated with the meaning/goal associated with recorded information), (ii) the material definition of the system based on the physical processes taking place in it; and (iii) a semiotic process of interaction among constituent components associated with the learning of how to keep coherence between the notional and physical identity in order to better express the emergent property on which they depend. Here reflexivity plays an important role in determining the willingness to keep of change a given identity. This is why it is essential to carry out quantitative analysis of the performance of cities in participatory way, because it is only by co-producing knowledge with the social actors that we can guarantee its quality.

The process of learning how to integrate information referring to notional and physical aspects of the system inside an autopoietic process is called a semiotic process (Peirce, 1935; von Uexküll, 1957; Pattee, 1982, 1995, 2013; Kampis, 1991; Kull, 1998). Social-ecological systems use a semiotic process for generating and reproducing their own identity by establishing an "idem and idem" relation between the meaning assigned to the notional definition of the identity – representing the goal of what has to be preserved - and the actions that have to be taken to achieve this result – representing the actual functional and structural elements operating in the system (Giampietro, 2018). After having introduced this additional concept we can finally define an identity of a city as *the ability of maintaining an impredicative relation between: (i) "the metabolic characteristics of the whole" – black box interacting with its context – determined by a given mix of constituent components; and (ii) "the metabolic characteristics of the constituent components" – parts interacting with each other within the black-box. This impredicative relation is maintained by an operational mix of realizations of holons*. The identity is defined in an impredicative way because the "characteristics of the whole" and the "characteristics of the constituent components" depends on each other and do affect each other in a chicken-egg relation. These concepts can be used to combine in an integrated analysis two non-equivalent logics of perceptions and representations of processors referring to both *functional* and *structural elements*.

### 3.1.4 Examples of the applications of these concepts to the analysis of the metabolic pattern of Barcelona

The message of the term holon is that when studying the organizational structure of complex metabolic systems, we cannot keep separated the analysis of the material and immaterial components. This means that we have to be aware that a complex system requires the simultaneous handling of two families of non-equivalent representations referring to the characteristics of:

(i) functional types - the notional description of the functional elements; and
(ii) structural types - the characterization of the structural elements.

However, it should be noted that the ambiguity associated with the concept of holon – a curse in reductionism – becomes a virtue in complexity science. In fact, this ambiguity can be used to establish a bridge between different quantitative representations based on the observed characteristics of “external referents” that can only be observed across different scales of analysis. An example of this fact is provided in Figure 3-1. The constituent components of Barcelona - the parts of the systems that must be reproduced to preserve the identity of the system and that decide about the activities to be performed in the city – are defined, in the analysis of human activity as: (i) residents; (ii) commuters and (iii) tourists. These choices of these constituent components are determining the set of expected functions expressed in the city. In the example in Figure 3-1 we consider the function of MOBILITY as one of the final causes associated with the constituent components. Then when considering a lower level of analysis the function of mobility, in Barcelona, is expressed by a combination of two holons: (i) “private mobility”; and (ii) “public mobility”. These are notional elements of the metabolic pattern to which we can associate specific processors (as described below a processor is a combination of inputs required to achieve a given task).

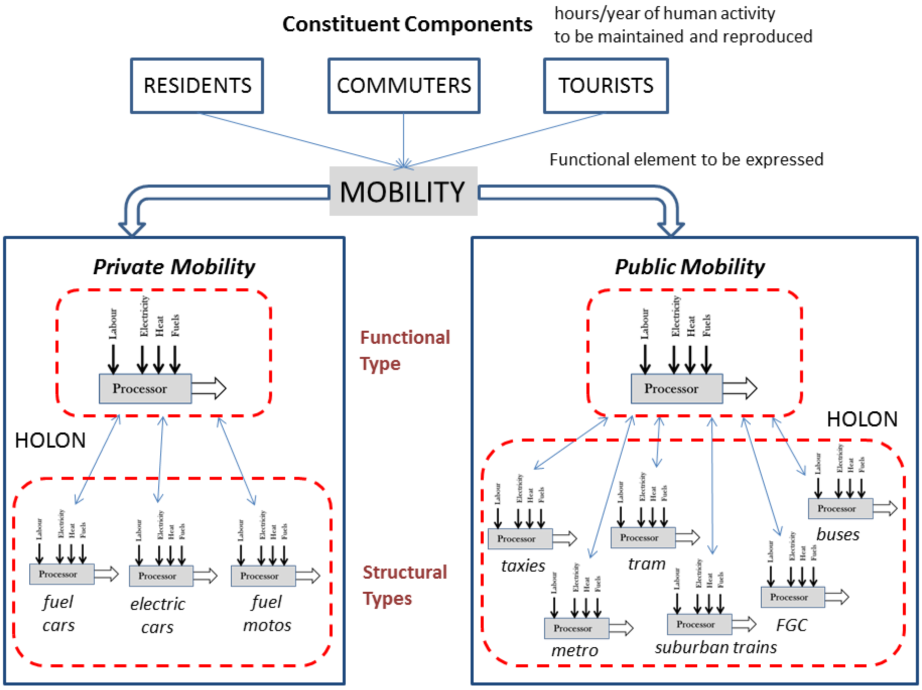


*Figure 3-1 The many-to-one mapping of structural and functional types in the representation of relations over structural and functional elements in the metabolic pattern of Barcelona*

It should be noted that quantitative assessment requires the pre-analytical identification of an external referent – the source of information making it possible to define the quantities of inputs required for mobility. The external referents for this assessment can only be defined at a lower level when observing the operation of structural types – e.g. in the case of public mobility by looking at both the occupancy of taxies, trains, metros, buses and other factors determining the overall consumption of energy carriers.

This is an essential feature of the approach we are proposing: the set of relations over functional and structural elements described across different levels of analysis makes it possible to utilize and integrate different sources of information about the function of mobility in Barcelona. A general definition of a ***final cause*** – mobility – can be split into two notional functional elements – "private mobility" and "public mobility" – that can be used as identities of holons. Starting from the identification of these holons we can characterize notional functional types that map onto structural types (e.g. taxies, trams, metro, etc.) used to fulfill the function. In this way, the quantitative analysis can be scaled up to functional processor in relation to the amount of hours/year of the fund of human activity (how many people are using these different means of public mobility). At the level of the structural elements – when observing the consumption of taxies, trams and metro) it is possible to gather data that can be aggregated – this is a bottom-up assessment. On the contrary at the level of the functional elements it is possible to gather data (but unfortunately not always) from statistical data about the characteristics of the functional elements considered as a whole – this is a top-down assessment. In this way, it becomes possible to combine (while double checking) different sources of information – either bottom-up or top-down. The procedure we followed in assessing the metabolic pattern of Barcelona is illustrated in details in Section 4. Based on the flow-fund scheme proposed by Georgescu-Roegen and adopted by MuSIASEM (Giampietro, Mayumi and Sorman, 2012) in this deliverable we are using two definitions of fund elements reflecting the adoption of two different dimensions of analysis to map the size of constituent components average values per year:

(i) when dealing with human activity the size of the constituent components is accounted in hours of Human Activity per year; and

(ii) when dealing with land uses inside the city the size of the constituent components can be accounted in units of areas defined in categories of Built Environment (Land Uses km$^2$ – when dealing with external area). In addition we use also another unit for measuring the activities inside buildings – m$^2$ of categories of Building Uses – when dealing with the assessment of internal areas.

The quantification of the extensive variable human activity is used to define the size of functional elements. An example is given in Figure 3-2.

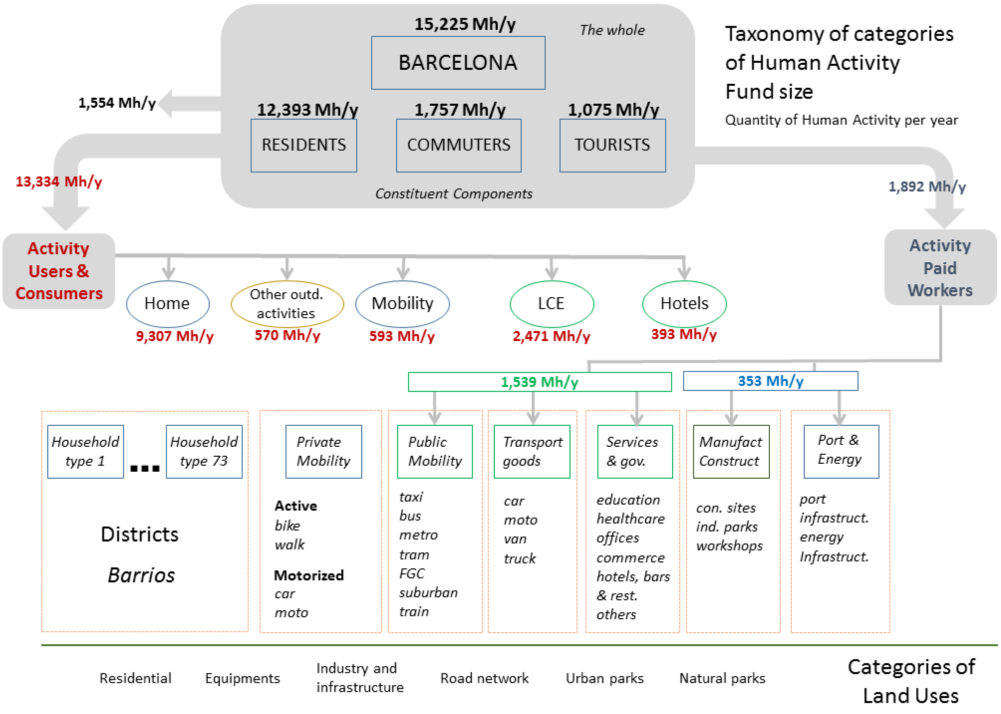


*Figure 3-2 The quantification of the size of the constituent components defined in terms of hours/y of human activity across the different functional elements of the metabolic pattern*

Looking at the relations over the data in Figure 3-2 we can see that the total of human activity of Barcelona is determined by the sum of: (i) the hours of human activity of the residents – i.e. number of residents multiplied by 8,760 hours/year and reduced by the hours of human activity of the residents outside the city borders; (ii) the hours of human activity of the commuters – i.e. those coming to work in Barcelona from the suburbs and spending additional day time in Barcelona for leisure, education and cultural activities; and (iii) the hours of human activity of the tourists. This amount of human activity is then split into two main categories:

1. human activity invested in ***Paid Work*** required **to supply** goods and services in the market. This labor is required to carry out the various activities in the public services, private services and industry and construction – this quantity is 1,892 Mh/year; and
2. human activity invested **Outside the Paid Work** sector in leisure, culture, education, unpaid work and physiological overhead (sleeping, eating, personal care)– 13,334 Mh/year - this human activity is required ***to consume*** the goods and services provided by the Paid Work sector.

Considering the split over these two categories is important because as flagged by Zipf (Zipf, 1941) human activity is a key input needed in socio-economic processes which has to achieve a dynamic equilibrium over two distinct tasks: (i) you need human activity (paid work) to produce goods and services; but also (ii) you need human activity (shopping, cultural activities, leisure, requirement of services and education) to consume goods and services. This is what makes it possible to reproduce and maintain jobs in the Paid Work sectors. For instance in Barcelona the tourists (a quantity of human activity invested in consuming) represent an important component of the economy.

> *"Expressed differently, in 1929, the United States discovered a new "raw material": leisure time, which in a way, is just as much a "raw material" as coal, oil, steel or anything else, because for many types of human activity, leisure time, is an essential prerequisite".*
>
> (Zipf, 1941)

Many of the human activities carried out in a city are services that requires the simultaneous investment (achieving a dynamic equilibrium) of two distinct types of human activity: (i) hours of human activity outside the Paid Work category – e.g. riding a bus, having lunch in a restaurant, taking a guided tour; and (ii) hours of human activity inside the Paid Work category - people working in the bus company, people working in the restaurant, people working in the touristic agency organizing the tour. This parallel accounting is illustrated in Figure 3-3. In our system of accounting we track the two quantities of human activity and this establishes an additional internal set of relations inside the expected values of the data set.

### *Tracking relations over functional definitions of categories of human activity*

A tool useful for organizing the quantitative (notional) characterization of the allocation of human activity using categories reflecting a functional point of view is a metabolic dendrograms illustrated in Figure 3-3. In the metabolic dendrograms we are defining the taxonomy of categories used for the accounting. We are also organizing the quantitative representation of the various categories on different hierarchical levels reflecting the notional order assigned to them. Looking at the dendrograms illustrated in Figure 3-3 the human activity of the whole (level n) is required to express the emergent property (reproducing Barcelona). As the definition of an identity for Barcelona (and its constituent components) cannot be assumed to be as uncontested it is essential that this type of definitions be made in an open space dialogue.

Then this human activity is split over the two complementing functions linked by an impredicative relation (production needing consumption and consumption needing production). The total amount of hours of the whole is split into “Paid Work” and “Outside Paid Work” (level n-1 on the right of Figure 3-3). Then moving again to the right to level n-2 we can list the various final causes shaping the activities in the two compartments. Therefore, the two quantities of hours of human activity divided into production and consumption split again:

(i) Paid Work is split into four functional elements: Services and Government, Port, Construction and manufacturing, Energy Sector under the condition of closure across levels – i.e. the sum of the hours of the lower level components (level n-2) must be equal to the size of the component Paid Work at the level n-1;

(ii) *Outside Paid Work* is split into four functional elements: Residential, Mobility, Use of SG, Other outdoor activities – under the same condition of closure on the relative size of the components across level n-1 and level n-2.

Finally when arrived to the levels of the dendrograms identifying functional elements it becomes possible to move to lower levels of analysis in which we can track the formation of holons. For example, the functional element Services and Government maps onto 7 functional elements: education, healthcare, offices, commerce, bars, restaurant & hotels, transport and other, which in turn map onto structural elements: transport of goods, maps onto 4 structural elements: cars, motorbikes, vans and trucks.

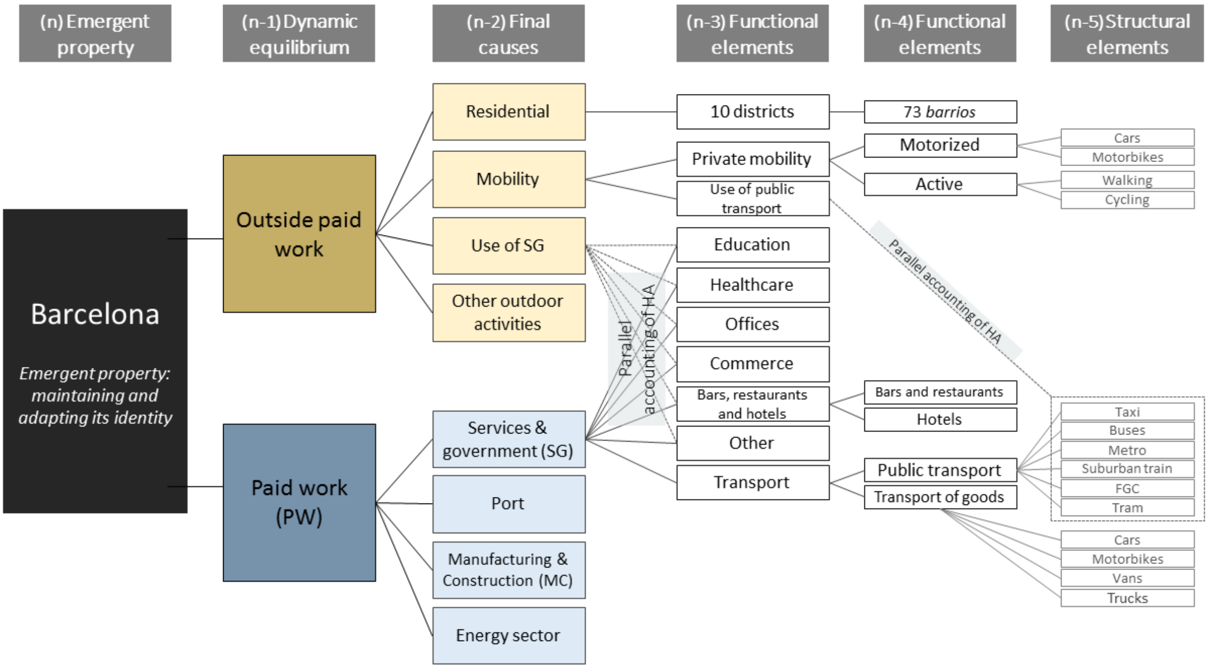


*Figure 3-3 The dendrograms of functional categories of human activity across levels*

That is, when considering the whole dendrograms we can start from the left with the "emergent property of the whole" – the identity of Barcelona – then we move right by making a distinction between activities related to the production of goods and services and activities related to the consumption of goods and services (the distinction proposed by Zipf). At this point it becomes possible to identify the different final causes associated with the activities of production and consumption. These final causes are then used (moving again to the right) to identify functional elements that are used to achieve the final cause. When reaching this level of disaggregation we can identify the holons (the set of structural elements used in the functional element to express the expected final cause). In this way, moving again to the right we can define additional categories of accounting (to describe processors) useful to describe the biophysical conversions taking place in the structural elements making part of the holon. In this way it becomes possible to track different chains of relations within the metabolic pattern. These chains can be defined within the consumption side: (i) Barcelona → Activities outside Paid Work → Residential → 10 Districts → 73 Barrios; and within the production side: Barcelona → Paid Work → Services and Government → Transport → Public Transport → Metro.

### *Tracking relations over structural definitions of categories of human activity*

A different way of tracking the relations over quantities of human activity is to check the behavior of constituent components: the structural elements – the different categories of people taking decisions about the activity to be carried out in the city. This is a different type of analysis aimed at knowing: WHO is doing WHAT, and HOW.

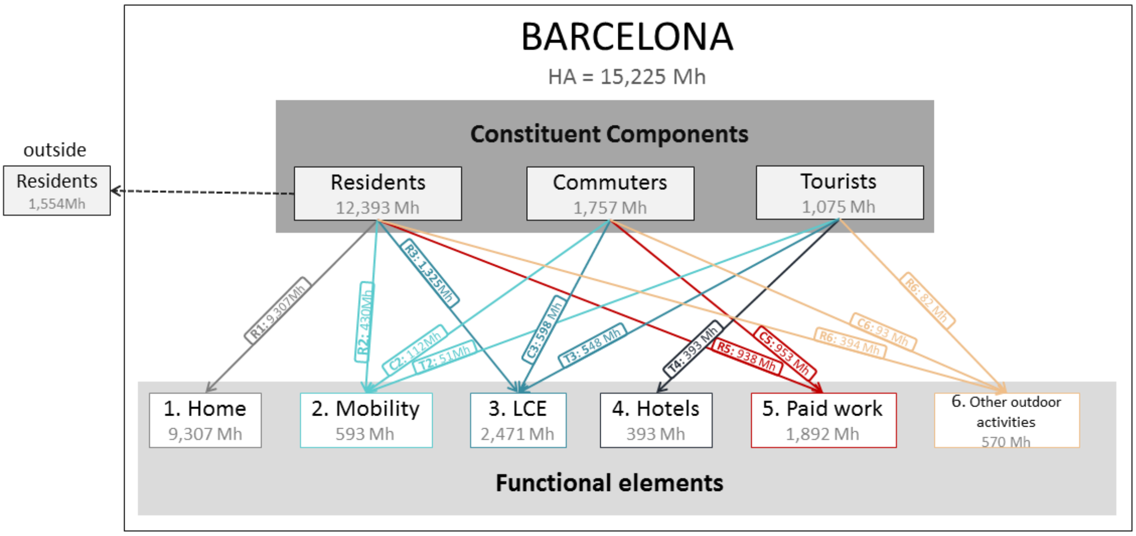


*Figure 3-4 Tracking the behavioral patterns of the constituent components through human activity*

In relation to this goal, we have to gather information about the behavior of the three groups of hours of human activity associated with the identities of the constituent components. This is shown in Figure 3-4. In the upper part of the figure we indicate the split of human activity on different functional elements, making possible to know who is carrying out which activity. For example: (i) tourists do not invest human activity in Paid Work; (ii) Paid Work in Barcelona is supported 50% by the activity of residents and 50% by the activity of commuters; (iii) Hotels are only used by tourist. Integrating the analysis of investments of human activity in the various categories of activities “Outside Paid Work” and in the various categories of “Paid Work” is important, not only for an analysis of energy performance of the city, but also because this analysis provides information about the sources of income of the people working in the city – i.e. the jobs associated with the supply of goods and services used by the consumption side. Commuters require different infrastructure of mobility than residents. Tourists, commuters and residents use different services.

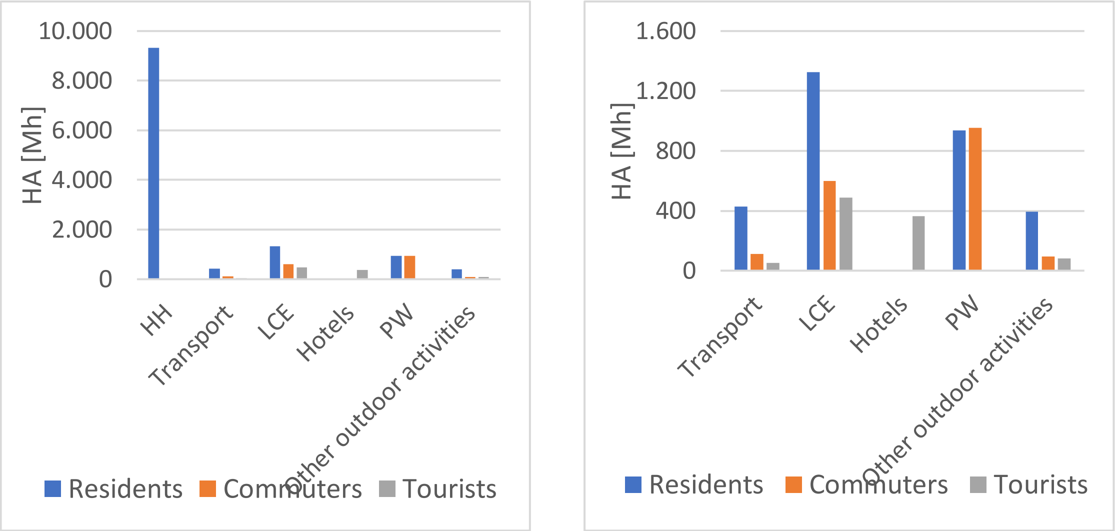


*Figure 3-5 Tracking the amount of investment of human activity of the constituent components*

### *Establishing an interface between analyses based on Human Activity and Useful Surface*

On the bottom of Figure 3-2 we have indicated a set of categories of Land Uses describing the metabolic pattern when adopting a dimension of analysis referring to the Built Environment. In fact, as discussed earlier, a non-equivalent way of describing the different constituent components of Barcelona is to map the total size of what is chosen to represent the whole size of "Barcelona" in terms of areas of categories of Built Environment. When choosing this different dimension of analysis the constituent components are no longer identifiable in relation to typologies of people, but identifiable in relation to typologies of land use. An example of the relations that can be established across these elements and the functional and structural elements is provided in Figure 3-6.

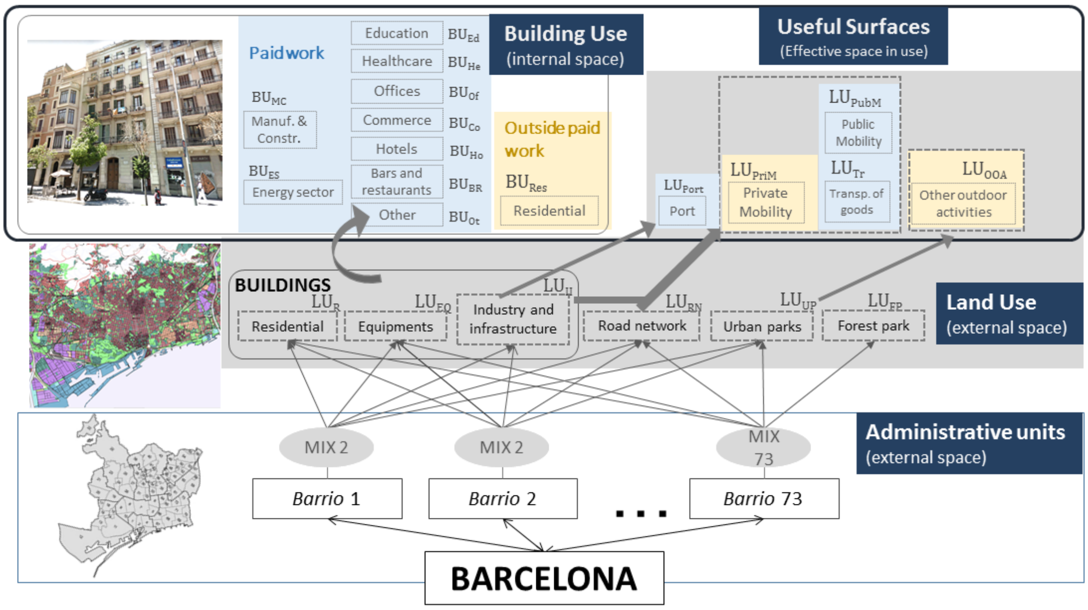


*Figure 3-6 The quantification of the size of the constituent components defined in terms of area of Built Environment/year*

In this case the classification of spatial elements there are three different logics that can be used to identify typologies of land use:

(i) *a functional logic – internal view* - in which the internal use of different typologies of buildings (categories of Building Use – $BU_i$) – i.e. residential, industrial building, commercial malls - are identified in terms of expected metabolic characteristics – e.g. kWh of electricity of appliance per m$^2$ of the apartment or MJ of heating per m$^2$ of the apartment;

(ii) *a functional logic – external view* - in which the areas of different typologies of Built Environment (categories of Land Use – $LU_i$) – i.e. residential, equipment, industry and infrastructure, road networks, urban parks, forest parks – are identified because their metabolic characteristics are relevant for the analysis – i.e. the density of flows of energy associated with their function. The identification of these typologies is used to define their geographic location inside the border of the whole city;

(iii) *an administrative logic* in which the identity and the size of the area is determined by their administrative boundaries (the identity has been given and it is not related to the typology of functional elements).

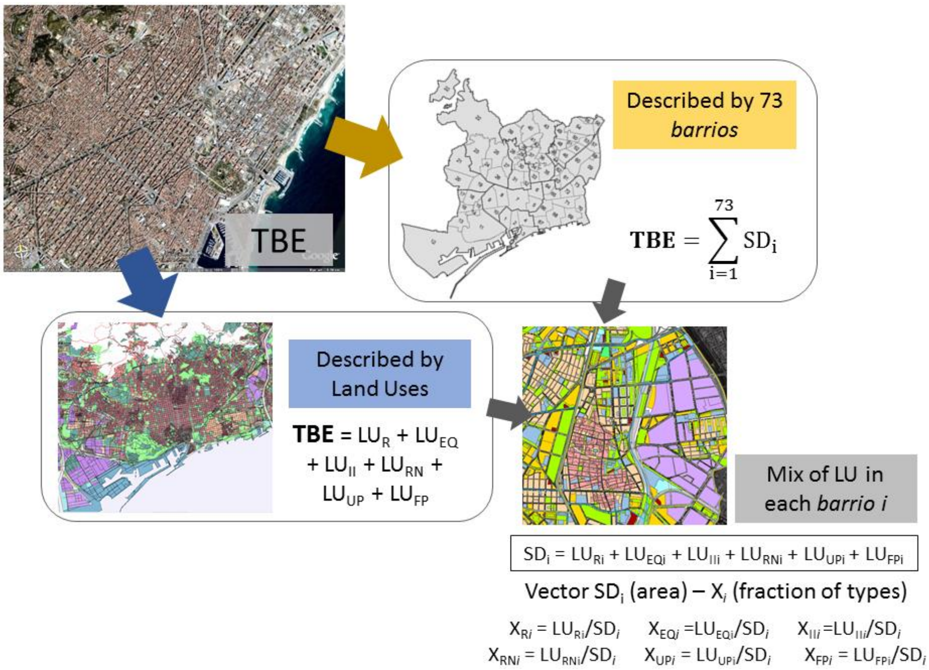


*Figure 3-7 The integration of the two methods of accounting areas in Total Built Environment: (i) TBE = ∑ SDi; and (ii) TBE = ∑ LUi*

As illustrated in Figure 3-7 these non-equivalent methods of spatial representations of metabolic characteristics can be integrated. The metabolic characteristics of a given district (administrative logic) can be defined as determined by a combination of the metabolic characteristics of the different typologies of Built Environment (functional) included in it. In this way, the metabolic characteristics of a district can be quantified by using a vector describing the profile of fractions of area expressing different typologies of Built Environment. This additional block of relations adds an additional layer of analysis to the characterization of the metabolic pattern of the city. However, it should be noted that, due to the exploratory nature of this study, in this deliverable we did not combine these categories as illustrated in Figure 3-7.

Even though we did not implement this type of analysis in our application it is important to flag the point made by Vaclav Smil (2015), that urban systems are dissipating energy at a density which is orders of magnitude higher than the density at which natural process (production of biomass) are supplying potential energy inputs. This implies that an analysis of the study of de-carbonization of cities should be based on a careful consideration of the dynamic balance between areas that can be used to catch primary energy sources (winds, solar, biomass), areas that are required to transform these primary sources into energy carriers, and areas that are required for the end use of these energy carriers to express the required set of functions.

In section 4 we illustrate the application of relational analysis to the metabolic pattern of a city and how the concept of holon can be used to establish a bridge between the two quantitative representations based on two dimensions of analysis: (i) a definition of size based on a taxonomy of human activity categories; and (ii) a definition of size based on a taxonomy of Built Environment categories. An example of this relation is given in Figure 3-8. On the top of the figure we have the categories of human activity mapping onto the notional definition of final cause and functional elements (as illustrated in Figure 3-2). This analysis can be linked to the analysis of the end uses required by the constituent components (as illustrated in Figure 3-4). On the bottom of the figure we have the categories of Built Environment that are used to identify typologies of land use inside the city. The definition of constituent components in this case is done using administrative boundaries – e.g. barrios. This is illustrated in the bottom part of Figure 3-8 in which 4 barrios (A, B, C, D) are represented as being composed by different combination of areas mapping onto a set of categories of Land Uses, defined inside Built Environment – in this example they are: Equipments, Residential Buildings, Industry & infrastructures, Road network, Urban park, Natural Park.

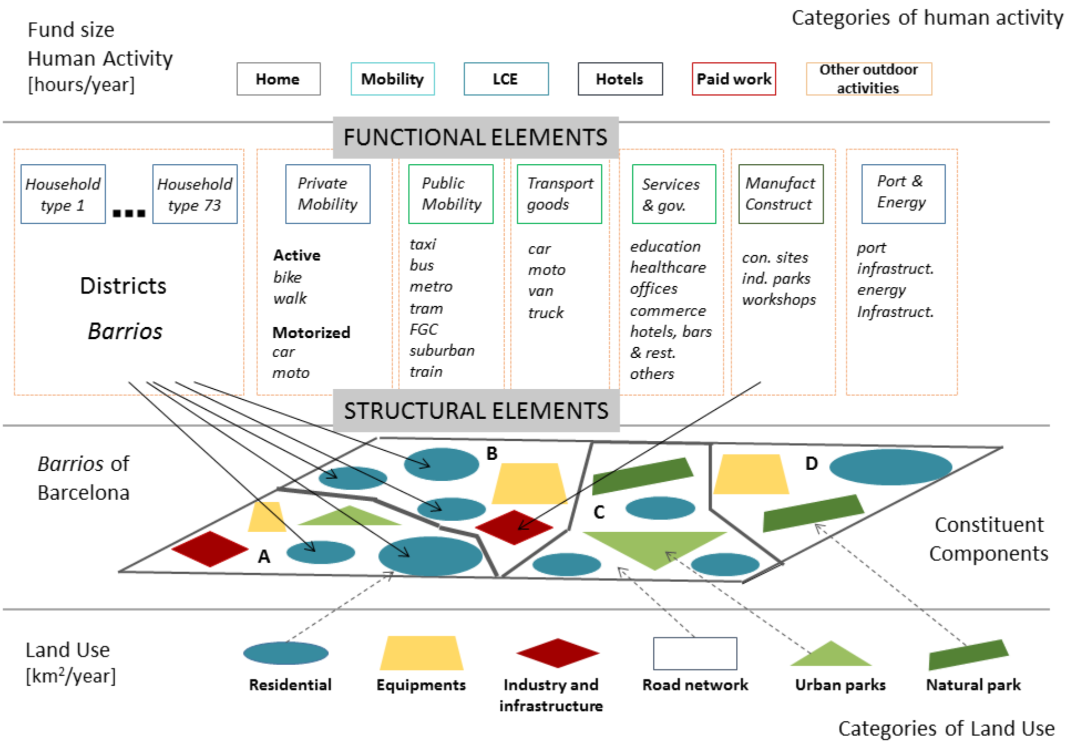


*Figure 3-8 The bridge provided by holons between an analysis of the metabolic pattern of cities quantified in relation to categories of Human Activity and Built Environment*

The overview given in Figure 3-8 shows the integrations of types of analysis: (i) the dendrograms of categories of human activity based on the notional definition of functional elements coming from the top; and (ii) the dendrograms of categories referring to spatial analysis reflecting the characteristics of the metabolic pattern based on the definition of structural elements. In this way we can establish a relation between data and information relevant for the socio-economic actors (on the top) and data and information relevant to define the external constraints determined by the availability and characteristics of urban spaces (on the bottom). Because of their "semantic openness" the definition of holons makes it possible to keep coherence in the handling of the two non-equivalent characterizations.

## 3.2 Identifying the epistemological challenges posed by the quantitative analysis of the energetic metabolism of social-ecological systems

### 3.2.1 What are the relevant aspects of the metabolism of cities that should be considered when quantifying their energy performance?

We illustrate in this section the application of relational analysis to the metabolic pattern of a city in conceptual terms. A quantitative application to the case of Barcelona is illustrated in Section 4.

We open this section using the wisdom of cybernetics. Cybernetics is the science of control concerned only with the functional aspects of a system, rather than with its material aspects. Cybernetics is relevant because it deals with the realm of notional systems: what type of information a regulator should know in order to be able to regulate a given system. In relation to this point, the first priority in cybernetics is to identify *the relevant features* that have to be characterized, monitored and controlled for achieving a given goal. When dealing with the regulation of a metabolic system the goal is to be able to express an integrated set of functions guaranteeing the maintenance and reproduction of the metabolic system itself.

So using the wisdom of cybernetics the first question to be answered is: what are the factors to be considered to characterize, monitor and control the behavior of a complex adaptive system like a city?

In relation to this goal the Law of Requisite Variety (Ashby, 1957) says that in order to characterize, monitor and control a complex system "*the variety of states of a control mechanism must be greater than or equal to the number of states in the system being controlled*". That is, it is not possible to study the performance of complex set of processes – i.e. the metabolism of a city – if we use a simple systems of monitoring and control – i.e. an overall assessment of "energy" consumption, or overall assessment of "emissions", or by adopting just an input/output index (using graphs with curves describing expected relations over just two variables). An effective analytical tool kit capable of generating sound information for policy and governance must have an adequate power of discrimination capable of finding relevant characteristics across different scales and different dimensions of analysis. In particular it must be able to identify: (i) which types of energy carriers are used; (ii) who is using them; (iii) how much energy carriers are used;

(iv) how are they used; (v) why are they used; (vi) where and when are they used. If we cannot characterize the system in relation to these aspects of the set of energy transformations taking place in the city it is very difficult to generate useful quantitative assessments for informing policy. In fact the energetic metabolism of a city consists of an intricate set of energy transformations across energy forms of different qualities taking place at different scales and levels of organizations, in different places at different times and for different purposes. In order to be useful the representation of this metabolic pattern requires a lot of detailed information and not just generic assessments of overall "energy consumption" or dubious and assumption dependent "level of emissions". This requirement of variety in the quantitative analysis of energy transformations was extremely clear to the pioneers of energetics in the 70's. They were claiming that: when dealing with the analysis of complex energy systems one has to diversify the accounting of different energy forms associated with different processes carried out in different places and at different times in relation to different types of inputs and outputs reflecting the co-existence of different goals(Leach, 1975; IFIAS, 1978; Maddox, 1978). Therefore, an effective energy analysis has to define an integrated set of indicators of performance and not just aiming at maximizing generic input/output ratios ("one size fits all") based on naive and simplistic definitions of efficiency (Smil, 2008; Giampietro, Sorman and Velasco-Fernández, 2017). Unfortunately, as discussed in Section 1 and 2, right now, this variety of assessments is difficult to find when looking at the analysis of the energy metabolism of cities.

In the rest of this section we want to flag three epistemological issues *that must be addressed in the pre-analytical phase* (before starting to crunch numbers) when carrying out quantitative analysis of energy transformations in order to assess the energy performance of a city. More specifically we want to illustrate the implications of the choice of: (i) metrics for accounting energy; (ii) levels and scales at which relevant transformations should be observed and represented; (iii) types of data – i.e. alfa-numerical in combination with spatial data (in GIS); (iv) the problematic assessment of emissions, which implies the unavoidable generation of contingent results – i.e. the assessments depend on the hypotheses chosen for the calculation.

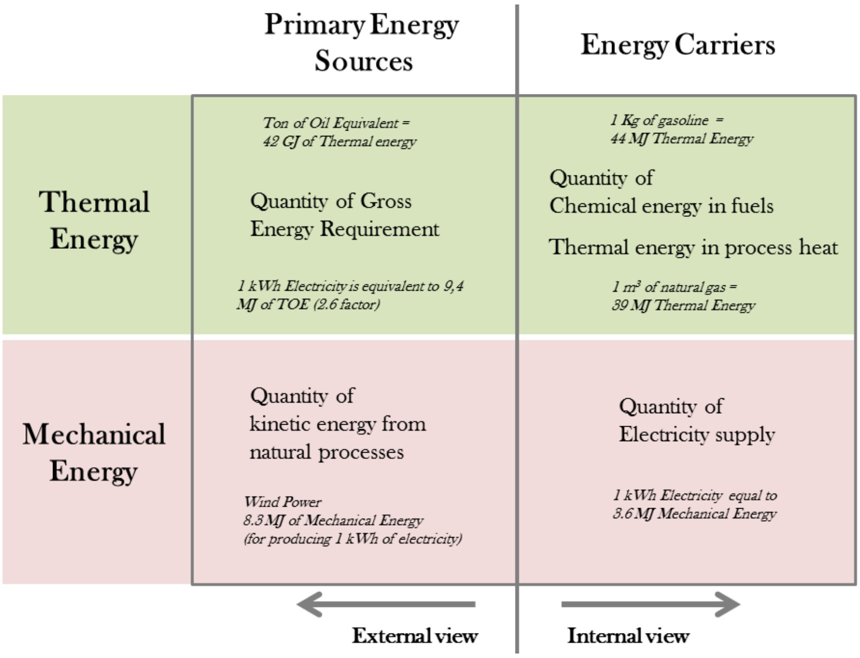
### 3.2.2 How to avoid a sloppy handling of different energy metrics

As mentioned earlier the quantitative analysis of energy flows describing the metabolism of either a country, an economic sector or a city requires the definition of a proper **Error! Bookmark not defined.**across typologies of energy forms (Giampietro and Sorman, 2012; Giampietro, Mayumi and Sorman, 2013).

In particular, three categories of accounting (defined below) are needed to properly assess quantities of energy inside the metabolic pattern of a social-system or a city: (i) Primary Energy Sources; (ii) Energy Carriers; and (iii) End Uses. In addition to these three categories of accounting referring to the functional role that energy plays in the metabolism, there are other categories reflecting the existence of qualitative differences among energy forms – e.g. thermal energy, mechanical energy, gravitational energy, chemical energy, etc.

When considering the supply side of the energy metabolism – how Primary Energy Sources are transformed into Energy Carriers - we can classify quantities of energy using four non-equivalent categories, when generating assessments referring to energy forms of different quality. The 2x2 matrix describing these categories is illustrated in Figure 3-9. This matrix reflects the existence of two distinct criteria determining qualitative differences in energy forms on the supply side:

1. the first distinction is between: (i) *primary energy sources* (PES) – energy forms that must be available in nature because they cannot be produced by humans; and (ii) *energy carriers* (EC) – energy forms produced by humans (taking advantage of the availability of PES). The production of EC requires the expression of *end uses* (processes controlled by humans);
2. the second distinction is between: (i) *thermal energy* – energy forms associated with the ability to generate heat; (ii) *mechanical energy* – energy forms associated with the movement of objects.



| | Primary Energy Sources | Energy Carriers |
|---|---|---|
| **Thermal Energy** | *Ton of Oil Equivalent = 42 GJ of Thermal energy*<br>Quantity of Gross Energy Requirement<br>*1 kWh Electricity is equivalent to 9,4 MJ of TOE (2.6 factor)* | *1 Kg of gasoline = 44 MJ Thermal Energy*<br>Quantity of Chemical energy in fuels<br>Thermal energy in process heat<br>*1 $m^3$ of natural gas = 39 MJ Thermal Energy* |
| **Mechanical Energy** | Quantity of kinetic energy from natural processes<br>*Wind Power 8.3 MJ of Mechanical Energy (for producing 1 kWh of electricity)* | Quantity of Electricity supply<br>*1 kWh Electricity equal to 3.6 MJ Mechanical Energy* |

*Figure 3-9 Different energy forms used to characterize the supply side of the metabolic pattern*

Therefore we can have 4 combinations of non-equivalent energy forms:

- (i) Primary Energy Sources thermal – e.g. coal, oil, geothermal;
- (ii) Primary Energy Sources mechanical – e.g. wind, hydro;
- (iii) Energy Carriers thermal – e.g. gasoline, natural gas;

(iv) Energy Carriers mechanical – e.g. electricity.

Quantitative assessments of these energy forms are non-equivalent – i.e. (i) mechanical energy is qualitative different from thermal energy; and (ii) primary energy has important characteristics making it "different" (it cannot be produced by humans) from secondary energy (it is produced by humans). This set of four distinct accounting categories is a source of major confusion in the use of quantitative assessments of energy flows (Giampietro and Sorman, 2012; Giampietro, Mayumi and Sorman, 2013).

In fact, it is possible to use different logics to establish conversion factors making it possible to move from a given quantitative assessment of an energy form to another. However, ANY TIME we use a conversion factor for moving across energy forms, the "meaning" and the usefulness of the resulting quantitative assessment changes. For example we can calculate, using the *Partial Substitution Method*, a *virtual quantity* of Joules of "energy" that can be associated with 1 kWh of electricity using the category of accounting "Tonnes of Oil Equivalent" (TOE). In this case we are calculating the amount of Gross Energy Requirement **thermal** (belonging to the category of Primary Energy Sources) that would be required to produce 1 kWh of electricity measured in the category "secondary energy mechanical". The logic of this conversion method is to calculate how much thermal energy in the form of a primary energy source would be required to produce a given quantity of electricity when using oil. However, this virtual quantity of TOE is only useful for this given purpose – i.e. in relation to the criteria of assessing a virtual gross energy requirement thermal equivalent. This conversion implies the loss of a lot of other useful information: TOEs calculated in relation to electricity produced with wind do not emit a proportional amount of $CO_2$ and cannot be used, as such, to power a refrigerator. The overview given in Figure 3-9 illustrates well how tricky could be the accounting of "energy quantities", especially when electricity is mixed together with other energy forms. We have always to contextualize the choice of the accounting category in relation to the purpose of the quantitative assessment. Using the categories presented in Figure 3-9 we can find four non-equivalent assessments associated with the same "quantity" (1 kWh) of electricity:

1. an assessment as an energy carrier (secondary energy produced by human controlled process and used under human control) – PURPOSE: we want to know the quantity of electricity getting into a refrigerator. This quantity belongs to the category of *mechanical energy* (electricity is a form of mechanical energy when considering its exergy value), and therefore the quantity is **3.6 MJ of secondary mechanical energy**;
2. an assessment as requirement of primary energy needed in its production (primary energy that cannot be produced by humans) – PURPOSE: we want to know how much wind energy (belonging to the category of mechanical energy – the kinetic energy of the wind) is embodied in 1 kWh. This initial requirement of

PES can be quantified as **8.3 MJ of primary mechanical energy** (2.3/1 is the chosen conversion of kinetic energy of the wind into electricity, but it depends on the characteristics of the technology – transformation and transport – and the wind resource);

3. an assessment of the overall gross energy requirement (primary energy that cannot be produced by humans of a reference form – thermal) – PURPOSE: comparing the gross energy requirement of different countries producing different mixes of EC using different mixes of PES. The normalization of the assessment across countries with different characteristics of their energy sector requires the choice of a type of Primary Energy Source used as standard (in the past it was Tonnes of Coal Equivalent, in these days it is Tonnes of Oil Equivalent). The standard conversion protocol, Partial Substitution Method, converts all the quantities of electricity independently of how they were produced into Gross Energy Requirement (thermal) using a common benchmark – 1 J of electricity = 2.6 J of TOE - the quantity of oil required to produce 1 J of electricity in a standard oil-fired power plant. When adopting this conversion factor 1 kWh of electricity is equivalent to **9.4 MJ of gross energy requirement (primary thermal energy)** – this is a virtual quantity useful only for comparison. Nowadays, many energy agencies are generating confusion when using TOE as a direct metric (unit) – i.e. 44 GJ - for energy carriers instead of its original use for accounting virtual joules of PES in Gross Energy Requirement (thermal). Then they use the equivalence of joules (1 J of electricity = 1 J of TOE) instead of the transformation coefficient derived from the thermal to electrical conversion efficiency (considering an efficiency of thermal power plant around 39% 1 J of electricity = 2.6 J of TOE).
4. an assessment as an energy carrier (secondary energy produced by human controlled process and used under human control) – PURPOSE: we want to know the quantity of heat (in a heather) can be generated by 1 kWh of electricity. In this case 1 kWh of electricity provides a thermal equivalent of 3.6 MJ thermal because its efficiency of conversion electricity/heat can be assumed to be close to 100%. In this case have a quantity of **3.6 MJ of secondary thermal energy** referring to the end use of the energy carrier.

This example flags the importance of keeping the accounting of different forms of energy separated. In these examples we have different assessments of the same quantity of a given energy form – 1 kWh of electricity - referring to three aspects: (i) how much PES (after having defined the type of PES) is required to produce the given quantity of EC; (ii) how much EC are we handling (or do we need) in the form of electricity; (iii) how much EC are needed to get a given result as End Use (e.g. electricity used for heating). Depending on the aspect considered as relevant the same quantity of electricity – 1 kWh – is accounted using three different numbers. This means that when considering different relevant attributes of performance – i.e. different typologies of end uses or different typologies of environmental impact –one should avoid as much as possible aggregating quantities of energy of different forms or using quantitative assessment of energy quantities not properly contextualized. Any aggregation of quantities of different energy forms into a common overall assessment (using conversion factors) implies the loss of potentially useful information and it is valid only in relation to the purpose behind the chosen conversion factor. As already noted, Joules of TOE do not map onto an equivalent quantity of emissions – e.g. in the case the electricity has been produced in a hydroelectric plant. In the same way, Joules of electricity cannot be used to fly a Jumbo jet like Joules of gasoline cannot be used to power a laptop.

The last two examples of the qualitative difference between Joules of fuels and Joules of electricity – useful for refrigerators but not for Jumbo jets - illustrates the importance of addressing another distinction over categories of energy accounting in relation to the requirement of energy. That is, we not only have to identify and use a set of categories of accounting making it possible to study the processes of supply of energy carriers:

1. the conversion PES → EC: this implies studying the characteristics of various steps of a chain **how** PES [defining **what** types of PES; **how much** of each PES, **which mix** of PES] *are converted into EC* [defining **what** types of EC, **how much** of each EC, **which mix** of EC];

but, also, we need to identify and use a set of categories of accounting making it possible to study the processes of consumption of energy carriers:

2. the conversion EC → EU: **how** EC [defining **what** types of EC, **how much** of each EC, **which mix** of EC] *are converted into* End Uses [defining **what** types of EU]. This requires identifying **who** is using EC, **how** and **why**. In relation to the pattern of consumption it is important to be able to characterize the end-uses as a profile of specific requirements of inputs (energy carriers and other production factors) associated with the expression of tasks and/or functions.

When considering the consumption side of the energy flows – how Energy Carriers are transformed into End Use – a proper classification become even more challenging.

Identifying the right categories of end uses represents an additional challenge for quantitative analysis, in fact, whereas is quite simple to measure quantities of energy carriers – e.g. a given amount of kWh or liters of gasoline - the definition of what are the “end uses” and their characterization requires the organization of data in data arrays. In order to organize an accounting capable of providing the required characterization we have to generate a taxonomy of end-uses identifying the functional (why) and structural (how) elements to which the end-use refers to. An example of the relation between a profile of inputs and the expression of a task is illustrated in Figure 3-10. In this example the end uses are profiles of quantities of “hour of labor; kWh of electricity; and MJ of fuels" required to perform a series of tasks (specific end-uses) defined within the gas and oil sector.

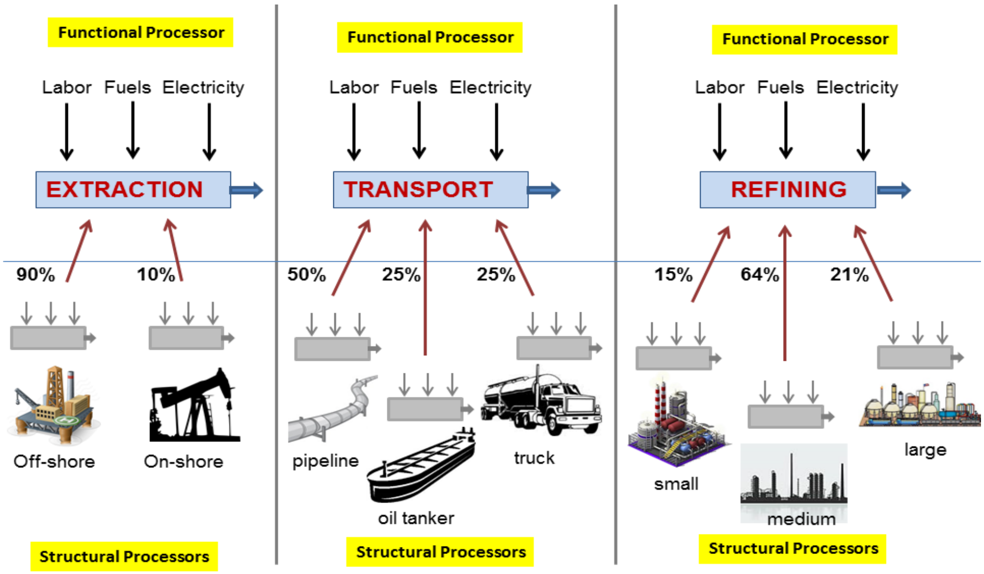


*Figure 3-10 Characterization of end-uses as a profile of energy inputs associated in relation to tasks defined in the oil and gas sector* (Aragão and Giampietro, 2016)

The approach of relational analysis makes it possible to operationalize the elusive concept of end use by introducing the concept of *processor*. In fact, a processor is defined as "an expected profile of inputs and outputs required to perform a given task" – i.e. to achieve a given end use. In this way, we can generate descriptions of how a given set of energy carriers has to be used, in a given combination with other production factors, in order to achieve a given goal.

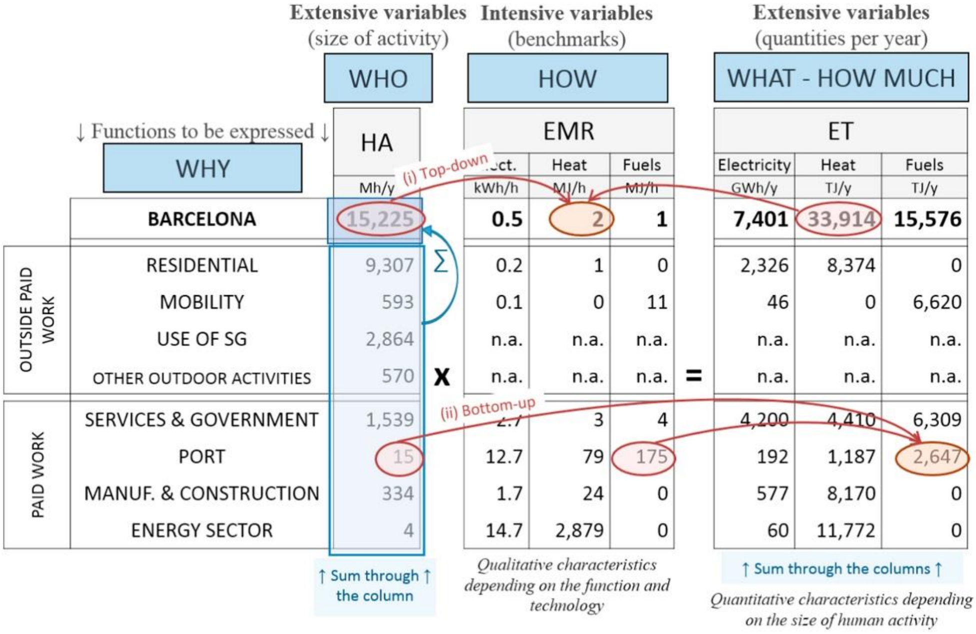
The concept of processor has another remarkable feature very valuable for metabolic analysis: it makes it possible to characterize the specific mix and combination of inputs (kWh of electricity, MJ of fuels, hours of labor) which is required to express functions or to describe the operation of structural elements across different levels of analysis. That is, we can define different types of processors for both functional and structural elements when analyzing the same metabolic system at different scales. As illustrated in Figure 3-10 we can calculate a processor: (i) for a functional element – e.g. "transport of oil" – a notional element which is not material; and (ii) for structural elements – e.g. "pipelines", "trucks", "oil tankers" – physical element which are material. That is, the concept of processor makes it possible to study the relation between a quantitative characterization of notional elements (functional types) and physical elements (structural types). This means that we can "scale" quantitative information inside the representation of the metabolic pattern from lower level to upper level and establish relations between patterns of requirement of energy carriers and pattern of expression of end uses in relation to the characteristics of both structural processors and functional processors. In this deliverable we illustrate how to carry out this analysis in relation to the metabolic pattern of a city.

### 3.2.3 Avoiding the excessive simplification implied by the concept of efficiency: how to define WHO is using, WHAT type of energy and HOW MUCH, HOW energy is used, and WHY

As discussed at length in the Deliverable 4.1 of Euforie (Giampietro, Sorman and Velasco-Fernández, 2017), the concept of efficiency is simplistic when used to study a complex metabolic system driven by human agency. This class of systems is also called “autopoietic systems” – i.e. systems producing themselves (Maturana and Varela, 1980). This definition clearly indicates that when studying the activity of these systems there is no measurable “output” that can be used to calculate an “output/input ratio”. When dealing with autopoiesis the concept of efficiency is not quantifiable. For example, talking of the “efficiency” of the metabolism of Barcelona, we should be able to define first of all what is “produced” by the energy used in Barcelona. In this case, the output of the process is not a specific biophysical output but rather an emergent property of the city: “the ability of reproducing the constituent components of the city expressing the expected functions associated with its identity” – a notional entity. In order to express this emergent property it is necessary to combine and integrate different activities (associated with biophysical processes) within Barcelona. These activities are taking place in different areas, at different times and across different levels of organization. This integration of activities and transformations across levels of organization, spatial and temporal domains is what we call the metabolic pattern of the city. This complex metabolic pattern cannot be described using a single number or a set of simple indicators, because these different activities can only be observed across levels at different scales of analysis. Therefore, in order to characterize the metabolic pattern of a city we have to develop a framework of accounting making it possible to identify the constituent components (the elements of the city that have to be reproduced) that are made of functional and structural elements (holons) that are integrating their activities in order to reproduce the whole city. We have illustrated examples of how to apply this framework of accounting to the analysis of Barcelona in the previous section.

If the concept of efficiency can only generate mono-criterial and mono-scale indicators (one at the time), we have to replace it with the concept of “performance”. Performance is a complex concept associated with a multi-criterial multi-scale characterization requiring the integration of different sets of relevant attributes. The concept of performance requires an integrated set of indicators referring to different criteria of performance that can be studied only by considering different levels and dimensions of analysis. But what type of quantitative information is required to characterize, monitor and control the performance of the metabolic pattern of a city? Is it possible to generate something new and different?

An overview of the organization of the quantitative representation proposed in our analytical tool-kit is provided in Figure 3-11. It does represent an innovative solution capable of organizing the quantitative information on the performance of the energetic metabolic pattern of cities answering simultaneously all the questions listed above: who is using energy, what energy is used, how much energy is used, how energy is used and why.



| | | HA | EMR | | | ET | | |
|---|---|---|---|---|---|---|---|---|
| | | | ct. | Heat | Fuels | Electricity | Heat | Fuels |
| | | Mh/y | kWh/h | MJ/h | MJ/h | GWh/y | TJ/y | TJ/y |
| | **BARCELONA** | 15,225 | **0.5** | 2 | **1** | **7,401** | 33,914 | **15,576** |
| OUTSIDE PAID WORK | RESIDENTIAL | 9,307 | 0.2 | 1 | 0 | 2,326 | 8,374 | 0 |
| | MOBILITY | 593 | 0.1 | 0 | 11 | 46 | 0 | 6,620 |
| | USE OF SG | 2,864 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| | OTHER OUTDOOR ACTIVITIES | 570 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| PAID WORK | SERVICES & GOVERNMENT | 1,539 | 2.7 | 3 | 4 | 4,200 | 4,410 | 6,309 |
| | PORT | 15 | 12.7 | 79 | 175 | 192 | 1,187 | 2,647 |
| | MANUF. & CONSTRUCTION | 334 | 1.7 | 24 | 0 | 577 | 8,170 | 0 |
| | ENERGY SECTOR | 4 | 14.7 | 2,879 | 0 | 60 | 11,772 | 0 |

*Figure 3-11 Simplified end-use matrix of energy carriers in relation to human activity*

This particular tool refers only to the use of energy carriers inside the city: the transformation of EC into End Use. For the sake of clarity, the example given in Figure 3-11 presents data referring only to two levels of analysis (the whole and the functional compartments) without describing functional and structural elements at lower levels. Examples of multi-level end-use matrix describing the system also at lower hierarchical levels of analysis are given in Section 4.

The information is organized in the form of data array follows the logic of the processor: each row describes the profile of inputs (elements of the cells) required to express a specific function. The top-row describes the processor of the whole system (Barcelona), whereas the lower level rows describe the processors of lower level functional elements. The label given to the row represents the "semantic output" of the processor – the task or function to be expressed.

Coming to the quantitative assessments (the numbers in the cell), the first cell (HA) of the first row describes the amount of Human Activity (HA) measured in hours per year (1 person = 8,760 h/year) which is required to reproduce and maintain the identity of Barcelona. This quantity of human activity does not map onto the number of people resident in the city because it includes also the activity of commuters (people coming every day to Barcelona to work), and the activity of tourists (people coming for short periods). The HA of residents is reduced by considering the activity of residents working or travelling outside the borders of the city. This first cell belongs to a column identifying WHO is using energy (people deciding the profile of human activities associated with consumption of energy). The last three cells on the right of the first row describe: (i) the amount of electricity consumed by Barcelona measured in GWh/year; (ii) the amount of heat consumed by Barcelona measured in PJ/year; (iii) the amount of liquid fuels consumed by Barcelona measured in PJ/year. These last three cells belong to three columns identifying both WHAT types of energy carriers are used and HOW MUCH energy carriers are used in Barcelona. The three cells in the middle are qualitative assessments that can be considered as benchmarks. They describe HOW energy is used in relation to the final cause associated with the label of the row (either for reproducing Barcelona as a whole of for expressing the expected functions in the lower rows). In this case, the label Barcelona indicates the goal of expressing the emergent property of reproducing the constituent components of Barcelona – i.e. expressing the integrated set of expected functions. The values of the data in these cells – kWh/hour of human activity; MJ/hour of human activity; MJ/hour of human activity – are related to the values of the data in the other four cells.

The relations across the quantitative values included in the end-use matrix can go in two directions:

(i) using data top-down – we can start from statistical data to fill the columns of extensive variables (the first and the last three columns) and then derive the values of intensive variables by dividing the total heat consumed in Barcelona (33,494 MJ/y) by the total human activity (15,225 Mh/y) and calculate the Exosomatic Metabolic Rate of $EC_{heat}$ ($EMR_{heat}$) as 2 MJ/h;

(ii) using data bottom-up – we can use estimation of the intensive variables describing HOW energy is used in a given compartment (175 MJ/h of fuels in the port) multiplied by the hours of work in the port (15 Mh/y) we can obtain HOW MUCH energy is consumed for that activity in the port (2,647 PJ/y).

The rows below the first one (Barcelona - level of the whole) are referring to a description of the metabolic pattern done at a lower hierarchical level (level of functional elements). At this level we can describe the metabolic characteristics – the processors - of the set of activities required for the reproduction of Barcelona. These eight functional elements are divided in two groups:

1. Outside Paid Work: (i) Residential, (ii) Mobility, (iii) Use of SG, (iv) Other Outdoor Activities; and
2. Paid Work: (v) Service and Government, (vi) Port, (vii) Construction and Manufacturing, (viii) Energy Sector.

When combined together these eight functional elements absorb for their end-uses the total amount of Human Activity and the total amount of the mix of Energy Carriers consumed in Barcelona. This condition of closure is very important for the system of accounting, because it generates a "sudoku effect" on the relations over the values of the numbers in the matrix (Giampietro and Bukkens, 2015). That is, this system of accounting imposes congruence constraints on the structure of data: (i) for extensive variables when summing all the lower elements of each column (quantities over 1 year) the sum must be equal to the total in the top cell (total quantity in 1 year); (ii) for intensive variables – the values of benchmarks (referring to bottom-up assessment) must be consistent with the horizontal expected relations over extensive variables (energy carrier consumption in a year divided by the hours of HA in a year) in each row.

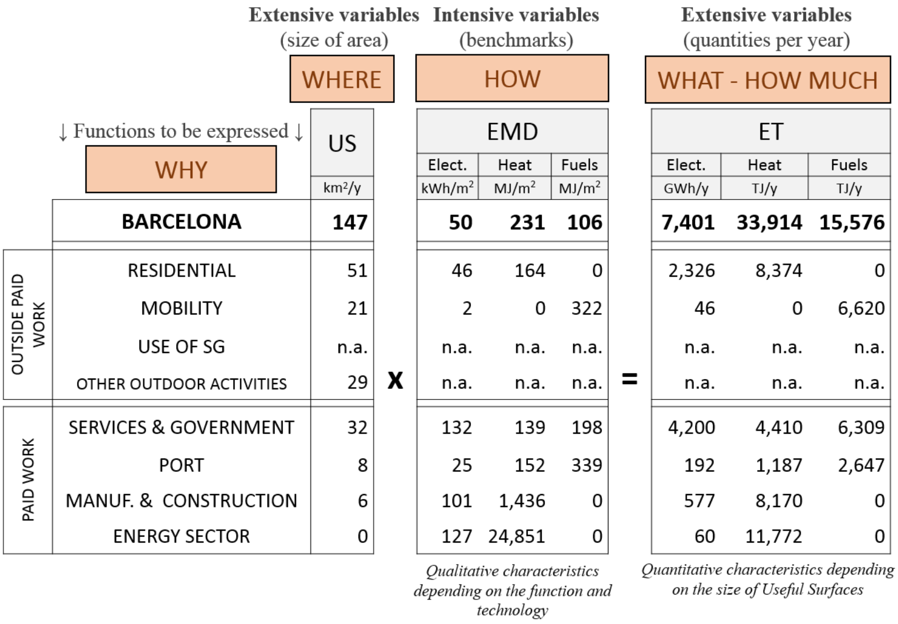
When looking at data organized in this way, we can realize that the processors of different functional elements of a city are quite different in relation to: (i) their size (when looking at the amount of human activity required in the various functional compartments); (ii) the profile of energy carriers they use (when looking at the amount of energy carriers required in the various functional compartments); (iii) the Exosomatic Metabolic Rates of the various carriers (the ratio energy carrier/hour of human activity). Inside Barcelona the various forms of energy carriers are used in different mixes at different speeds, for different purposes. Therefore, this visualization can help identifying the relevant factors determining the metabolism of the city: which activity is the largest consumer of which type of energy carrier? Why is this consumption necessary? How is the city expressing this function when comparing the benchmark with other cities?

Coming back to the discussion over the analysis of performance (or efficiency for those that like using this concept) this matrix illustrates clearly that the information needed to formulate policy is an information referring to the characteristics of the processors associated with the expression of different end-uses. We can only assess the quality of a technological solution (the performance or the efficiency) in relation to an identified function or task to be expressed such as: private mobility, residential, public mobility, construction. The more we analyze the metabolic pattern at a low level of analysis – in relation to specified tasks – the more we are capable of identifying and comparing "apples with apples and oranges with oranges". Looking at this organization of data it becomes extremely clear that policies based on assessments of aggregated levels of consumptions or emissions (as done in the Covenant of Mayors discussed in Section 1) are not properly informed about the specific characteristics of the cities they want to regulate.

We want to stress again that this deliverable is presenting preliminary data generated while exploring a new approach. Therefore, some of the data given in Figure 3-11 are rough approximations reflecting the simplification of the chosen representation. Here we are not claiming to provide reliable results nor do we want to explain how to generate this end-use matrix (this is done in Section 4). The only goal of this figure is to illustrate the possibility of organizing, in a coherent way, quantitative information in order to identify and keep separated the various pieces of information needed to characterize, monitor and control the performance of a city, in relation to its use of energy.

### 3.2.4 How to handle the co-existence of non-equivalent types of data – e.g. GIS vs alfa-numerical

Last but not least it is essential to acknowledge that, as discussed earlier, a quantitative analysis of the performance of a city must be based on an integration of alfa-numerical data (used to describe the relations within socio-economic data) and spatial data (used to describe the relations with ecological processes) to be handled in GIS. For this reason, the list of questions considered in the previous section – *WHO is using WHAT type of energy and HOW MUCH, HOW energy is used and WHY* – has to be expanded including an additional question: WHERE are these activities and transformations of energy taking place?



| | | US | EMD | | | ET | | |
|---|---|---|---|---|---|---|---|---|
| | | | Elect. | Heat | Fuels | Elect. | Heat | Fuels |
| | | km²/y | kWh/m² | MJ/m² | MJ/m² | GWh/y | TJ/y | TJ/y |
| | **BARCELONA** | **147** | **50** | **231** | **106** | **7,401** | **33,914** | **15,576** |
| OUTSIDE PAID WORK | RESIDENTIAL | 51 | 46 | 164 | 0 | 2,326 | 8,374 | 0 |
| | MOBILITY | 21 | 2 | 0 | 322 | 46 | 0 | 6,620 |
| | USE OF SG | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| | OTHER OUTDOOR ACTIVITIES | 29 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| PAID WORK | SERVICES & GOVERNMENT | 32 | 132 | 139 | 198 | 4,200 | 4,410 | 6,309 |
| | PORT | 8 | 25 | 152 | 339 | 192 | 1,187 | 2,647 |
| | MANUF. & CONSTRUCTION | 6 | 101 | 1,436 | 0 | 577 | 8,170 | 0 |
| | ENERGY SECTOR | 0 | 127 | 24,851 | 0 | 60 | 11,772 | 0 |

*Figure 3-12 Simplified end-use matrix of energy carriers in relation to spatial density.*

The inclusion of spatial analysis requires considering an additional dimension of analysis categories (new external referents of our observations), which implies the adoption of a new set of categories of observable attributes needed to give a different context to the assessment to be included in the end-use matrix. An example of this different end-use matrix is given in Figure 3-12.

When considering spatial analysis we can characterize the density of the consumption of energy carriers in relation to areas of built environment. We can do that by using the same structure of end-use matrix shown in Figure 3-11 by replacing the fund element against which to map energy flows: the fund *Human Activity* (HA measured in hours/year) against areas. As discussed earlier this operation implies addressing the co-existence of different logic used to define Useful Surfaces. We can refer the energy flows to internal areas (inside the building), what we called categories of Building Use; or to external areas (the land surface of the city), what we called categories of Land Use in the Built Environment. For this reason, the end use matrix shown in Figure 3-12 does not refer to the total area of Barcelona (the Total Built Environment, TBE) but to the sum of Useful Surfaces calculated summing a sub-set of Land Use (external areas) and Building Use (internal areas). For this reason we are using a label for defining the size of Barcelona in this end-use matrix called *Useful Surface* (US measured in $km^2$/year). In this end use matrix the vector referring to Human Activity - [human activity, electricity, heat and fuels] included in Figure 3-11 has been replaced by a vector characterizing an assessment of area of Useful Surface. The new vector is: [useful surface, electricity, heat and fuels].

Moreover, the internal area of Building Use does not map onto the “external land surface of the building”. When dealing with multiple-storey buildings the internal area used inside the building is larger than the land area occupied by the building. Various factors – built/non-built area, type of buildings and multi-storey index – can be used to assess the relation between the useful surface of internal areas in buildings ($BU_i$) vs external areas (land use - $LU_i$). Again, we did not do this type of analysis in this study and we want to stress again that the data shown are for illustrative purposes only. They are reflecting the simplifications of the chosen representation. The goal of this figure is to illustrate the possibility of organizing data in a more effective way.

When comparing the two end-use matrices illustrated in Figure 3-11 and Figure 3-12, we can see that the numbers in the matrices are based on the use of non-equivalent external referents – the extensive variable used to describe the size of the categories of human activities (hours/year) and categories of useful surface ($m^2$/year, $km^2$/year). However, the two matrices share a common set of external referents – the extensive variables used to describe the categories of energy carriers throughputs ($ET_i$/year) on the right. Therefore, they can be considered as two non-equivalent visualizations (when considering the intensive variables/benchmarks) of the same set of energy transformations.

### 3.2.5 The tool-kit needed to address the different aspects of the sustainability of the energetic metabolic pattern (direct, indirect, and embodied consumptions/emissions)

Recalling the discussion done in Section 3.1.1., the assessment of embodied emissions requires facing a well-known set of epistemological problems – e.g. truncation problem, joint production dilemma, impossibility to define in an uncontested way the boundary of open systems, the co-existence of two methods of assessment – based on typologies of conversions or the analysis of instances of conversions (Giampietro, Mayumi and Sorman, 2013). For this reason, the assessment of embodied emissions heavily depends on the choices made by the analysts. Thus, they will generate hypocognition (Lakoff, 2010): each of the chosen framings focuses on a relevant aspect but it implies missing others. We can say that an integrated tool-kit for the analysis of the performance of the metabolic pattern of a city has to include at least two different tools (we are not considering monetary implications here):

#1. A tool capable of analyzing the WHY, WHAT, HOW, HOW MUCH and WHERE of the energy transformations based on energy carriers taking place inside the city.
In the narrative of non-equilibrium thermodynamics this means characterizing the process of internal production of entropy associated with the maintenance and reproduction of the identity of the city: **dSi**. We already presented the tool for this goal – the end use matrix – in Figure 3-11 and Figure 3-12.

#2. the characterization of **the direct consumption of energy carriers** and Primary Energy Sources. **Direct emissions** are determined by the conversion of Energy Carriers into End Uses inside the city and the use of Primary Energy Sources to produce energy carriers inside the city. **Indirect emissions** are determined by the transformation of Primary Energy Sources into Energy Carriers taking place outside the borders of the city. By summing the two types of emissions we can calculate the **environmental pressure** associated with energy transformations. In the case of Primary Energy Sources based on fossil energy their exploitation does also imply depletion of stocks. The scheme used to carry out this analysis is given in Figure 3-13.

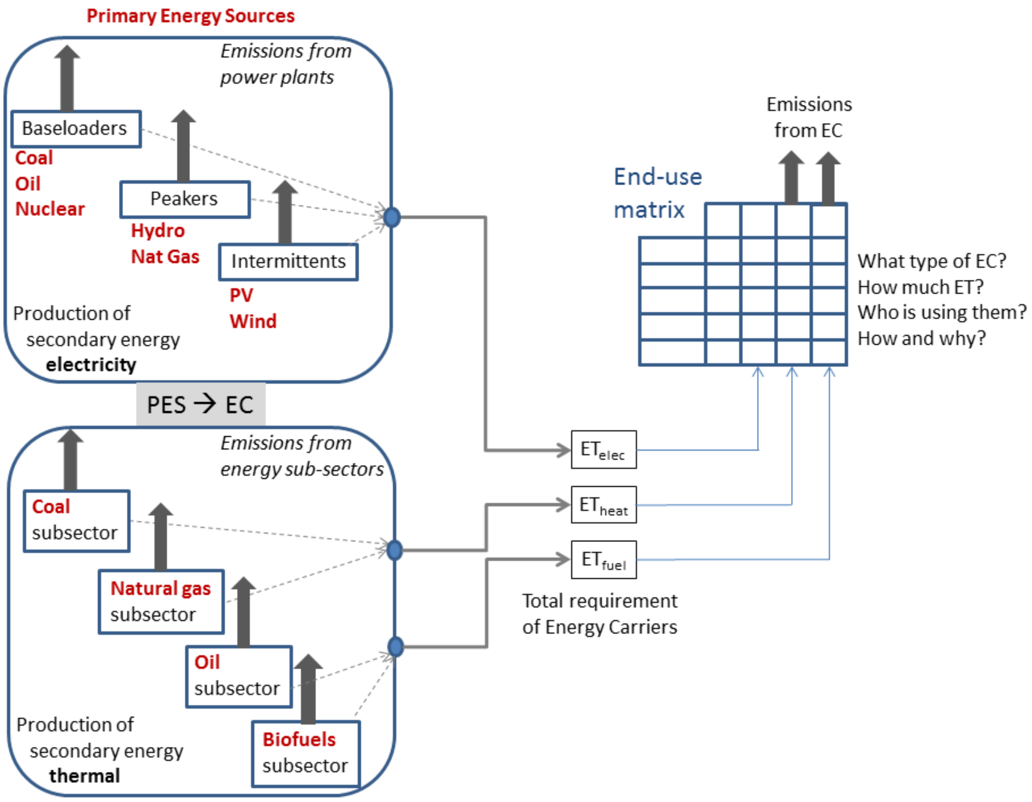


*Figure 3-13 The overview of the role of the end-use matrix and the direct (consumption of secondary energy – EC) and indirect (consumption of primary energy – PES)*

It should be noted that in general the production of EC based on PES is not carried out inside the city borders (for practical reasons and for pollution reasons). Even thought, in the case of Barcelona there is a small power plant (peaker) operating in the port. Therefore, the emissions associated with the production of energy carriers are mainly referring to processes taking place outside the borders of the city. In this case, these indirect emissions are embodied in the imported energy carriers. When dealing with the assessment of embodied emissions, there are two options available:

1. an assessment based on available knowledge of typologies of conversions – in this method one assigns standard processors (technical coefficients based on "unitary operations") to different typologies of power plants required for generating the required mix of energy carriers – i.e. using standard benchmarks. In this way it becomes possible to estimate the direct emissions associated with the consumption of energy carriers in the city, after specifying: (i) the mix of Primary Energy Sources used for producing the EC mix; and (ii) the technical coefficients of the various typologies of power plants required by the mix;
2. an assessment based on available knowledge of specific instances of conversions – in this method one tracks the origin of the imported energy carriers consumed in the city. In this way it becomes possible to identify the power plants of origins

and then use the technical characteristics of these plants to calculate the overall level of emissions. Unfortunately, it is not always possible to track the origin of the energy carriers – e.g. who produced the electricity or the fuels (when, where, how), which is consumed in the city.

An overview of the relations considered in this type of analysis is given in Figure 3-13. However, there is another type of emissions associated with the city related to the energy carriers used to produce the goods and services imported by the city.

The scheme in Figure 3-14 shows clearly that the total amount of emissions associated with the metabolic pattern of a city could be obtained by summing: (i) direct emissions (associated with the consumption of the carriers and primary energy sources inside the borders); (ii) indirect emissions (associated with the production of the energy carriers outside the city); and (iii) embodied emissions (associated with the production of imported products). Therefore, the emissions of a city do not depend only on the amount and quality of energy carriers consumed within its border. Additional factors to be considered (not always known) are: the mix of primary energy sources used to produce the energy carriers used for producing the imported inputs and the technologies used to produce them.

Coming back to the direct emissions, the location and density of metabolic emissions of the different end-uses can provide useful information to the study of air quality. Many other factors, such as emissions not related to the direct burning of fuels, sewage water treatment, emissions due to the burning of wastes, emissions not related to the direct burning of fuels could be included in the end-use matrix as a non-energy emissions. In the analysis presented so far, we did not consider the energy required to build the power capacity used in the energy sector (embodied energy). However, this can be done (depending on the purpose of the analysis), and then the assessment of embodied energy consumed in the construction of the plant has to be discounted on the life span of the plants.

The distinction between direct, indirect and embodied emissions shows the importance of characterizing the level of openness of the city. In fact, we can calculate a **local environmental pressure** determined by direct emissions, and an **externalized environmental pressure** determined by indirect and embodied emissions. This externalized pressure is associated with the production of energy and non-energy imported goods and services produced outside the borders of the city. In this way we can assess the effects of externalization on other social-ecological systems (both on the environmental and on the socio-economic side). In fact, imports are convenient from a biophysical point of view for the city because they not only avoid local emissions, but also the requirement of additional production factors (labor, water, soil, mineral) that are embodied in imported goods and services. This type of analysis can be based on the information given by an externalization matrices – e.g. by estimating the emissions using the characteristics of “virtual processors” required to produce the imported goods. As a matter of fact, the imports of the city include many other typologies of inputs beside energy carriers as for example food and consumable and durable goods. So, it would also be important to calculate the indirect and embodied consumption of energy and emissions for all the imports of a city. A scheme of this type of analysis is given in Figure 3-14.

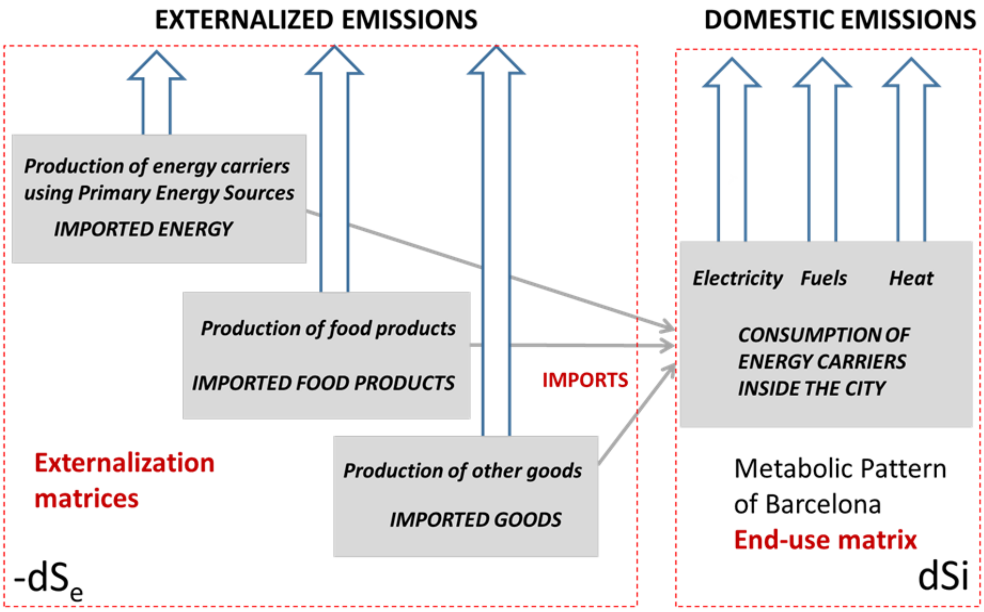


*Figure 3-14 Externalization matrices to assess the emissions associated with imported inputs*

The approach illustrated in Figure 3-14 is being implemented, at the moment, using the same approach presented in this deliverable in another EU project MAGIC ([http://magic-nexus.eu/](http://magic-nexus.eu/)). In MAGIC the approach is applied at different scales to analyze the metabolic pattern of EU countries addressing the implications of externalization using externalization matrices. In MAGIC it is the whole NEXUS between water, energy and food that is analyzed following the logic presented here.

Studying the implications of externalization is relevant for two reasons:

1. *for ethical reasons* – because the externalization of the requirement of natural resources, environmental services and other production factors (labor, technology, land uses) has an effect on both the health of other ecosystems, stocks of resources and the material standard of living of people living in other countries;
2. *for security reasons* – because the level of openness of the system is directly proportional to the level of dependence of the welfare of the city on the stability of the boundary conditions. That is, the more a social-ecological system

> (including cities) depends for its metabolism on inputs generated by processes outside its direct control, the more its identity depends on factors outside its control. Put it in another way, the definition of "security" both for a country and a city is associated to the protection of its very identity. In fact, Lippmann defined security as follows: "*a nation is secure to the extent to which **it is not in danger of having to sacrifice core values**, if it wishes to avoid war, and is able (...) to maintain them by victory in such a war*" (Lippmann, 1943).

The concept discussed so far clearly illustrate the complexity of the pre-analytical decisions required to implement an analysis based on externalization matrix. This analysis requires a pre-analytical discussion of the assumptions to be used for generating estimations, which in turn depend on the purposes of the analysis. Because of this fact, in this EUFORIE deliverable, we present only:

(i) the procedure to be used to define an end use matrix capable of characterizing the energy performance of a city, populating the matrix with data using the case study of Barcelona; and
(ii) a general illustration of the procedure to be used to calculate the indirect and embodied emissions (and consumption). In this case, we did not populate the matrix with data, because this operation would require the involvement of the users of the analysis through participatory processes.

## 3.3 Wrap-up of the material presented in this section

### 3.3.1 Using a semantic procedure to organize the quantitative assessments

We have illustrated a logical process that can be used to establish, in semantic terms, a set of expected relations over functional and structural elements across different levels of organization. These relations can be used to integrate non-equivalent data sources in a quantitative representation of their metabolic characteristics.

The procedure implies different steps that imply an impredicative definition of quantitative assessments:

***STEP #1 - Identifying the constituent components of the city and their size***

The IDENTITY of the city depends on the mix of the functional and structural elements whose maintenance and reproduction is required to preserve "the whole". Two dimensions have been chosen - Human Activity and Built Environment - to identify constituent components – the elements whose size determines the size of the whole. Human activity is used to identify final causes, because the identity of a city depends on the choices of activities made by the people living in it. The geographic characteristics of the area in which the city is located are also important because they constraints the possible solutions to be adopted for the Built Environment.

Using these choices, the size of a city can be measured either in:

(i) hours of Human Activity/year - this quantity is mapping onto *endosomatic* flows associated with the activity of human beings – food, water, solid waste and sewage – and onto “exosomatic” flows associated with the capability of humans to command and control of devices – electricity consumed by a laptop, material products for construction. That is human activity represents an input of control for the proper expression of activities carried out by machines, but it requires physiological processes inside the human body; or

(ii) area of Built Environment associated with a given set of Land Uses and, as discussed earlier, a given set of Useful Surface and internal Building Uses.

The decisions determining the profile of human activity in the city can be described: (i) at the level of the whole – at this level the identity of Barcelona refers to the collective story-telling about the meanings associated with that name (something impossible to quantify); (ii) at the level of constituent components we have to consider:

- the structural side of human activity - we identified three categories of people - residents, commuters and tourists – as constituent components. They are individual story-tellers about the role that they play in Barcelona. The definition of a size in terms of human activity depends on the identification of the functional types of human activity found in the city (what the people expressing the functional types in the city do). That is, we have to estimate the hours of labor including those of the commuters and the activities of residents outside the city in order to be able to define the actual size of human activity inside the city;
- the structural side of the Built Environment – we identify two non-equivalent logics for defining constituent components within the Built Environment: (i) the metabolic characteristics of categories of areas: categories of accounting labelled $LU_i$ when referring to Built Environment, internal Building Uses when describing activities taking place inside buildings, and Useful Surface when referring to an undifferentiated sum of useful areas; and (ii) the administrative boundaries of districts and *barrios* (the categories of accounting are labelled $SD_i$). Their identities have been defined in administrative terms and their metabolic characteristics depend on the mix of $LU_i$ included in their areas.

### *STEP #2 - Identifying the final causes associated with the constituent components of the city*

After having defined the fund elements (determining in quality and size the constituent components to be reproduced) we have to define the WHY of the transformation of energy – why the people belonging to the constituent components do what they do. This requires defining the final causes associated with the maintenance and reproduction of constituent components. This analysis starts with a definition of two sets of final causes associated with: (i) the production of goods and services; and (ii) the consumption of goods and services in the city. The identification of two sets of final causes makes it possible to identify at a lower level of analysis different sets of FUNCTIONAL ELEMENTS associated with them. In turn, the definition of functional elements makes it possible to "translate" the implications of the final cause into a definition of functional types. This translation means identifying the holons operating in the city. The holons are combinations of functional and structural types realized within functional elements.

### *STEP #3 - Identify the expected couplings of functional and structural types within the holons*

After having defined the various holons inside the functional elements, we have to analyze the HOW (how they do what they do) in relation of the WHAT (what they use to do what they do). At the level of the definition of the functional elements, we are capable of identifying the set of FUNCTIONAL TYPES – i.e. typologies of processes associated to tasks/outputs required by the functional elements – that have to be associated with sets of STRUCTURAL TYPES – i.e. typologies of organized structures used for expressing a task/output required by the functional type. Last but not least, it is essential to answer also the question WHERE. In relation to this question, the structural elements of the HOLONS can be used to define their location and size measured as units of area/year and to map them against different geographic definitions of categories of Built Environment – i.e. Land Uses, Building Use, administrative units.

### *STEP #4 - Multilevel mapping of functional and structural elements at different levels/scales*

It is at this point that the concept of exosomatic metabolism enters into play. Endosomatic energy transformations (metabolism of food inside the human body) do not require the use of technology or other external inputs beside the human body, food and water. On the contrary, human activity in the energetic metabolism of modern societies has the role of controlling exosomatic flows of energy – i.e. energy converted under human control by devices operating outside the human body – e.g. engines, machines, appliances. This implies that when dealing with exosomatic energy conversion, we can use the concept of processor – a vector indicating an expected set of inputs in which the quantity of human activity required for control is associated with various quantities of different typologies of energy carriers – to characterize the metabolic characteristics of specific activities. That is, when describing activities based on the use of exosomatic energy we can use the set of relations described in an end-use matrix (Figure 3-11) in which the Exosomatic Throughputs of specific energy carriers ($ET_i$) can be put in relation to the quantity of human activity (the size of the control $HA_i$). This relation translates into the definition of the specific profile of benchmarks (intensive variables):

$$EMR_{ij} = \text{Flow of energy carrier}_j/\text{hour of human activity}_i$$

In this way we can define a metabolic processor as coupling of metabolic fund types and metabolic structural types:

- a fund size ($HA_i$) and a set of flows ($\Phi_j$) → set of flow/fund benchmarks ($EMR_{ij}$) - $\Phi_j$/hour
- a fund size ($LU_i$) and a set of flows ($\Phi_j$) → set of flow/fund benchmarks ($EMD_{ij}$) - $\Phi_j$/area

Finally, it is essential to check carefully the level of openness of the system by comparing the size of the flows consumed internally and the flows exchanged with its context. In fact, the activities carried out inside the city – what is included in the end-use matrix – cover only a small fraction of the resources required by the city to stabilize its metabolism: the resources needed for food products, water inputs, energy carriers, material products. At times even services provided in the city are externalized - e.g. call centers, on line shopping. So in order to proper frame the analysis of the metabolism of a city it is important to have a clear idea of: (i) internal consumptions of energy carriers; (ii) the consumption of primary energy sources used to produce the carriers; (iii) the level of externalization of requirement of production factors – by checking the fraction of the internal inputs consumed in the end-use matrix that are produced inside the city versus the fraction imported from the outside.

### *STEP #5 - Gather data from different sources (external referents) to fill the sudoku*

Due to the impredicative nature of this assessment the definition of the semantic structure of accounting and the set of logical rules used to identify functional and structural components is the result of a process of learning by doing. Starting with available data one can start checking the consistence of the quantitative results with the structure of accounting and the expected relations. By applying this procedure it is possible to achieve two major results helping to achieve a sound crunching of numbers in the quantitative analysis:

(i) it makes it possible to identify external referents – potential sources of available data which refer to measurements of attributes and/or characteristics of processes taking place in the city across different dimensions and levels of analysis;

(ii) it generates redundancy in the information space (generation of mutual information in the data set). The various layers of relations across quantitative values make it possible to generate a "sudoku effect" in the data array that can be used to verify the robustness of data. This makes it possible to use "triangulations" to estimate the "same value" using different sources of data across different expected relations. In this way it becomes possible to fill empty cells in the matrix when reliable data are not available or double check the robustness of estimated (or statistical) data. Moreover, as explained in Section 4, the end-use matrices shown in Figure 3-11 and Figure 3-12 are examples of a *multi-scale end-use matrix*. This means that each row of the matrix – e.g. the vector describing the metabolic characteristics of the Services can be opened becoming a lower-level end-use matrix in which the characteristics of the functional elements are characterized as determined by another "sudoku effect" applied to a series of vectors describing the metabolic characteristics of lower-level functional elements. Examples of this analysis multiscale are described in detail in Section 4.

### 3.3.2 The usefulness of the tool

The approach for studying the energy performance of cities presented here can be applied to identify and characterize the metabolic profile of the structural and functional elements. More specifically it can:

(i) contextualize indicators of performance on the requirement side: the benchmarks describing the performance of "heating in building" or "mobility" can be contextualized in relation to the typology of the city – e.g. a city with a very cold weather, or very sparsely populated city. This refers to the "requirement of end uses" – why energy is used by whom to do what. The benchmarks for the functional element – "residential heating" - in Reykjavik and Naples are obviously different exactly like the relation between private and public mobility is different in Tokyo in Japan (with a very high density of the population) and in Phoenix in Arizona (with a very low population density);

(ii) identifying options and constraints in relation to well identified tasks on the supply side: after having identified separately the functions to be performed and the structural types used to express these functions, it becomes possible to identify options for improvement. This refers to the "option space of production processes" – how energy carriers are produced, from which primary energy sources and how. The same final cause (producing electricity) can be achieved using different functions (baseloader and peaker power plants), the same function (baseloader production of electricity) can be expressed using different structural types (nuclear and coal power plants) and the set of structural types can be improved (new typologies of power plants).;

Comparing the performance of different cities looking for best practices requires a proper contextualization of the whole metabolic pattern, matching requirement with supply in order to generate indicators of performance capable of comparing “apples with apples and oranges with oranges”. After having contextualized at which level we are studying improvements for the energy transformation and which is the expected effect over the overall consumption compared with others possible improvements, the analysis of best practices will result more effective for discussing the desirability of the considered options. This makes it possible to evaluate the effect of different factors affecting the overall performance of a city in an integrated and meaningful way. This is especially important to avoid discussions in which different sides “throw numbers to each other over the fence” (an expression coined by Jeroen van der Sluijs), without having reached an agreement on how to establish a relation among the non-equivalent indications given by these numbers.

In conclusion the relational analysis across levels and dimensions of the metabolic pattern of cities makes it possible to generate an integrated set of performance indicators that can be chosen à la carte in relation to the specific purpose of the analysis and the specific characteristics of the city under analysis. An overview of possible quantitative indicators that can be used for identifying typologies of city and for assessing their energetic performance in relation to different functional elements is given in Table 3-1.

*Table 3-1 Factors to consider when comparing the performance of cities*

***In relation to spatial analysis within the Built Environment***

The characterization of the city should be based on a taxonomy of categories of Land Uses ($LU_i$ external area around the buildings) and categories of Building Use ($BU_i$ – internal area used in the building). Therefore, pieces of information used for comparison should include:

(i) taxonomy of $LU_i$, $US_i$ and $BU_i$;
(ii) profile of $LU_i$, $US_i$ and profile of $BU_i$;
(iii) ratio Buildings/Non-Buildings,
(iv) Natural Land Covers/Built Environment;

Indicators based on these pieces of information should be assessed at different hierarchical levels of analysis: the whole city, districts, *barrios*, individual buildings (outside and inside).

***In relation to the density of population***

(i) Total Human Activity/Total Built Environment;

Indicators based on this information should be assessed at different hierarchical levels of analysis: the whole city, Districts, *Barrios*

***In relation to typologies of Human Activity***

The characterization of the city should be based on:

(i) taxonomy of structural elements (e.g. resident, tourists, commuters),
(ii) profile of structural elements (e.g. relevance of commuters, relevance of tourists)

***In relation to climatic conditions***

The characterization of the city should be based on type of climatic conditions (e.g. cold, temperate, hot, wind situations, typhoons, heat waves, etc.)

***In relation to the context of the metabolic pattern***

The characterization of the city should be based on:

- economic aspects such as: (i) GDP p.c.; (ii) mix of economic activities; (iii) mix of Jobs;
- biophysical factors such as: (i) national trade; (ii) international trade; (iii) mix of PES; (iv) availability of natural resources;
- demographic aspects such as: (i) demographic structure; (ii) homogeneity
- social aspects such as: (i) level of services; (ii) security; (iii) inequality; (iv) quality of institution;
- geographic aspects such as: (i) one the sea (port); (ii) on a big river; (iii) isolated; altitude; etc.

***Benchmarks for holons***

Performance indicators can be associated to benchmarks referring to the metabolic characteristics of functional elements: i.e. (i) EMRi – EMDi. The profile of HAi per capita per year and the density of human activity (HADi) in the various end uses represent additional indicators to include in the characterization of the metabolic pattern.

# 4 Illustrating the implementation of the approach with the case study of Barcelona

(Lead author Laura Pérez Sánchez)

## 4.1 An introductory description of Barcelona

Barcelona is the second most populated city in Spain and the 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. It has a Mediterranean climate, with warm summers and mild winters, and rain during spring and autumn –Figure 4-1.

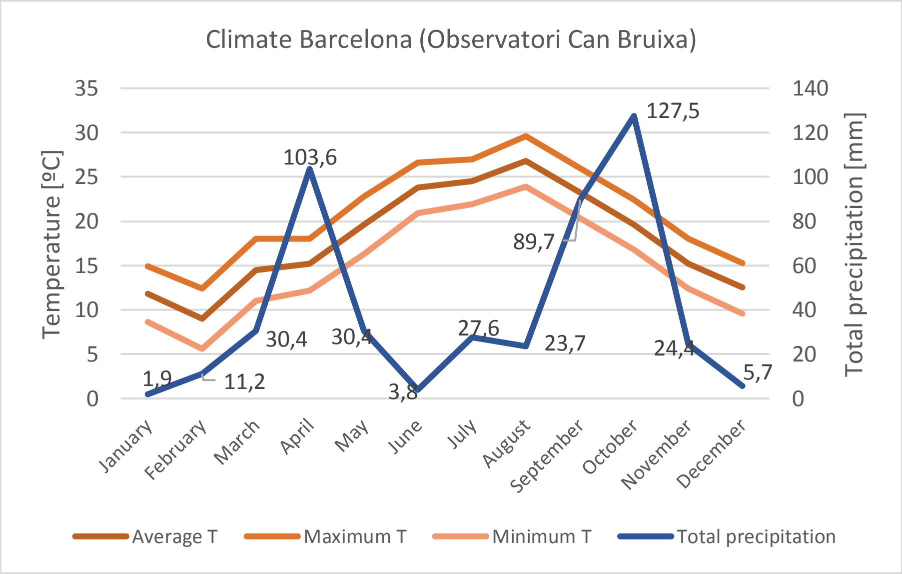
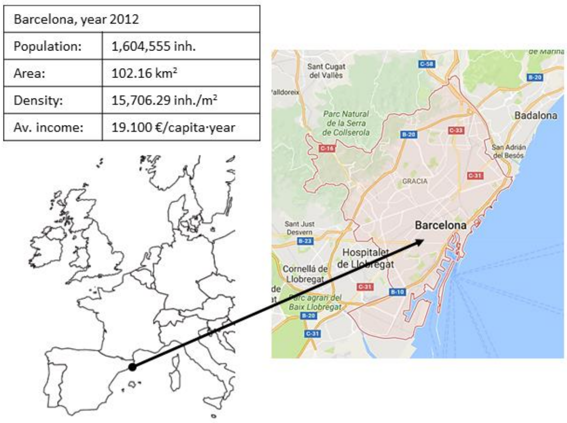


*Figure 4-1 Climatic parameters of the city of Barcelona (Ajuntament de Barcelona, 2012a)*

With a population of 1,604,555 inhabitants in 2012 and occupying 102 km$^2$, it is one of the densest cities in Europe. It is divided in 10 administrative districts and 73 *barrios* (Ajuntament de Barcelona, 2012a). *Barrios* are heterogeneous in size, age, type of construction, availability of services, demography, etc., and they also show income differences, visible in Figure 4-3, with the richest *barrio* having an estimated average income per capita almost 6 times higher than the poorest. The demographic structure of the city is the typical for a developed country (Figure 4-4), with an ageing population and an important flux of international immigrants since the 1990s.

Representing a 21.2% of the population and a 34.6% of the GDP of Catalunya, Barcelona is the centre of a metropolitan area (AMB), which has some administrative functions. Most of its population is living in the urban agglomeration around Barcelona, whose urban fabric is continuous.



| Barcelona, year 2012 | |
|---|---|
| Population: | 1,604,555 inh. |
| Area: | 102.16 km$^2$ |
| Density: | 15,706.29 inh./m$^2$ |
| Av. income: | 19.100 €/capita·year |

*Figure 4-2 Location and general data of Barcelona, 2012. Data from* (Ajuntament de Barcelona, 2012a)

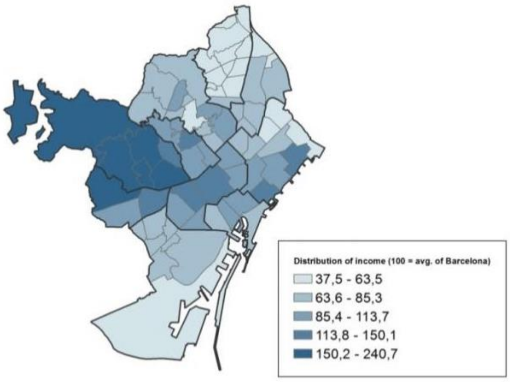


*Figure 4-3 Map of the barrios and the distribution of income per person in relation to the average value of the city (100 = 19,000€/year·capita). Data from* (Ajuntament de Barcelona, 2012a)

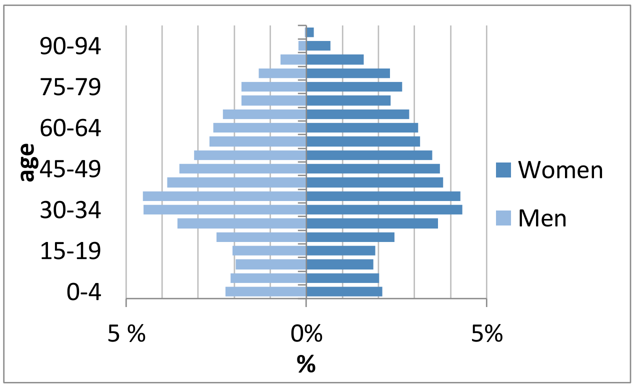


*Figure 4-4 Demographic structure of Barcelona, 2012. Data from* (Ajuntament de Barcelona, 2012a)

The fact that the city is surrounded by other smaller cities, a characteristic shared by many metropolitan areas, sets a strong land limitation and competition inside the boundaries of the city. At the same time it generates large amounts of commuting between municipalities.

The AMB had 3,299,500 inhabitants in 2012 (Àrea Metropolitana de Barcelona, 2012), and an important number of daily commuters from and to Barcelona (IERMB, 2014). The motorized trips in a day for the year 2012 divided between internal trips and those connecting Barcelona with other municipalities (Table 4-1) show the relevance of the intermunicipal mobility, and so, the large openness of the system in terms of population, which is going to be a relevant aspect when defining the human activity of the city.

*Table 4-1 Trips made in a working day inside Barcelona and from or to Barcelona* (IERMB, 2012a)

| **Trips** | **Internal** | **From or to Barcelona** |
|---|---|---|
| *Active* | 2,851,461 | 73,624 |
| *Public transport* | 1,452,569 | 881,179 |
| *Private transport* | 663,051 | 772,026 |

As it can also be seen in Table 4-1, this mobility is not only made by car or motorbike, the city is the centre of a wide network of public transport (bus, metro, tram, train, etc.) connecting radially the different municipalities in the AMB. This significant level of mobility is important since it makes it possible that only a 49,6% of the workers in Barcelona are resident in the city (data of 2012), and that a 25,4% of the residents in Barcelona worked outside the city (Ajuntament de Barcelona, 2012a). In absolute numbers, there are more workers in Barcelona living outside Barcelona than residents of Barcelona working outside it. That is, Barcelona is an attractor of workers.

The city shows high density of activities and a mixture of land uses, with spread small commerce and households in apartment buildings not higher than 8 or 9 floors. However, there is some centralization of uses, such as shopping malls and industrial areas at the outskirts in the north and south of the city.

The main economic sector is the service sector both in monetary terms and in number of workers. The manufacturing sub-sector is losing importance in the economy of the city (Barceló and Solà, 2014), and for this reason there is little information on the specific activities that is carrying out. In fact, the old industrial warehouses left empty in recent times are being occupied by tertiary activities such as logistics, Media, ICT (Information and Communication Technologies), Energy Companies, Design and Medical Technologies (especially in the so-called 22@ *barrio*).

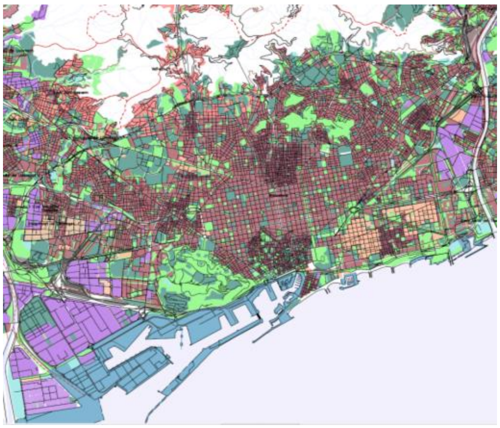


*Figure 4-5 Map of land uses of the metropolitan area of Barcelona* (Institut d'Estudis Territorials and Secretaria per a la Planificació Territorial, 2010)

Logistics has a strategic importance, because of the presence of the port. The port of Barcelona is one of the most important ports in Spain and the Mediterranean Sea, both in terms of passengers and goods. Fishery can also be found among the activities of the port, but in 2012 it just represented an approx. 4% of the fish consumed in the city (Port de Barcelona, 2012). An idea of the volume of exports and imports is given in Table 4-2.

*Table 4-2 Exports and Imports of the Barcelona province in 2012* (S.G. Estudios y Evaluación de Instrumentos de Política Comercial, 2017)

| | Exports | | Imports | |
|---|---|---|---|---|
| | ton | M€ | ton | M€ |
| 1. Food and stimulant industry | 2,638,244 | 3,849.8 | 8,281,878 | 6,854.1 |
| **2. Energy products** | **533,909** | **371.5** | **7,598,898** | **4,154.2** |
| 21. Coal | 8,969 | 1.8 | 160,177 | 19.9 |
| 22. Oil and its derivatives | 522,653 | 340.9 | 2,750,563 | 2,129.3 |
| 23. Natural Gas | 2,285 | 1.8 | 4,688,158 | 1,994.8 |
| 3. Raw materials | 1,165,023 | 666.6 | 1,888,838 | 1,077.3 |
| 2. Semi-processed and intermediate products | 8,457,199 | 14,525.7 | 6,431,274 | 15,150.6 |
| 5. Capital goods | 1,096,521 | 8,653.0 | 965,843 | 10,687.6 |
| 6. Automobiles | 945,379 | 8,284.9 | 916,770 | 6,646.9 |
| 7. Consumer durables | 133,609 | 780.4 | 282,082 | 1,668.0 |
| 8. Consumer goods | 568,665 | 5,929.2 | 869,333 | 8,345.4 |
| 9. Other goods | 1,433,817 | 2,383.2 | 291,918 | 357.1 |

In the same port and with the natural gas import facilities, there is a combined cycle power plant, which is the only large-scale electricity generation plant inside the boundaries of the city – Figure 4-6.

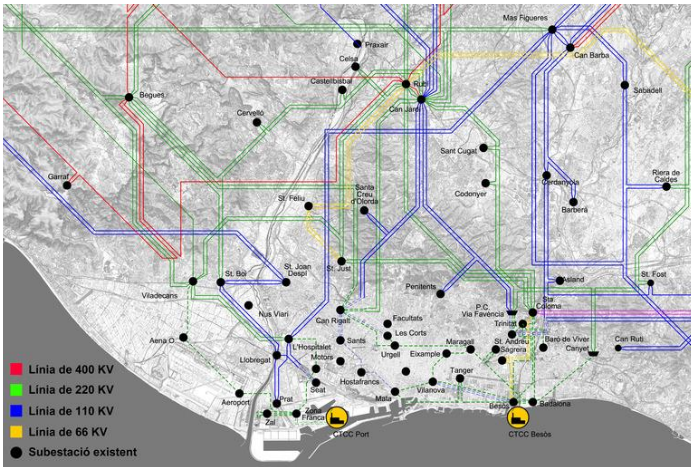


*Figure 4-6 Location of power plants in the city of Barcelona*

## 4.2 The structure of the information space and data sources

### 4.2.1 Introduction

In this section we will explain the organization of our data set: the data used in the end-use matrix to organize and visualize the internal metabolism of Barcelona. As explained in Section 3, the rationale behind our system of accounting acknowledges that "*the map is not the territory*" and that "*all models are wrong, but some are useful*". Therefore, what we do not intend to do is to provide as the result of this study the quantitative representation illustrated in the rest of this section with figures and tables. This representation depends on a series of assumptions judged as acceptable and reasonable by us, the analysts. What we present in this section is a methodology generating an integrated package of quantitative results based on a method that keeps an open and transparent record of all the choices taken before and during the quantitative analysis. This information space makes it possible for other people, who may disagree with the choices of framing or the strategies of quantification, to criticize the choices, propose alternatives and develop their own characterizations.

As we have already defined, the boundary chosen for this study is the administrative domain of the city; the study refers to the activities taking place in Barcelona during the year 2012. As the total amount of Human Activity refers to people that are continuously getting in and out of our system, the size of the city cannot be defined in relation to a static amount of people (the residents). At the level of a city, the important movement of people getting in and out implies requires acknowledging the fact that the Total Human Activity (THA) taking place in the city cannot be assessed by multiplying the number of residents by their annual hours of human activity (8,760h/cap·year). Therefore, we are defining the Human Activity associated with the metabolism of the city as the activities happening inside and related to groups of people defined as constituent components.

The variables used in the system in the case study of Barcelona are those in Table 4-3, explained in Table 4-4.

*Table 4-3 Data array of indicators used in the analysis of Barcelona*

| Extensive var. | | Intensive variables | | | | | | | | Extensive variables | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HA | US | EMR$_{elec}$ | EMR$_{heat}$ | EMR$_{fuel}$ | EJP | EMD$_{elec}$ | EMD$_{heat}$ | EMD$_{fuel}$ | EUSP | ET$_{elec}$ | ET$_{heat}$ | ET$_{fuel}$ | GVA |
| Funds | | Flow/Fund | | | | | | | | Flow | | | |

*Table 4-4 Description of the indicators used in the analysis of Barcelona (intensive variables are averages per year)*

| **Indicator** | | **Definition** | **Unit** |
|---|---|---|---|
| **HA** | Human Activity | time invested in end-uses per year | h |
| **US** | Useful Surfaces | quantity of area devoted to end-uses | km$^2$ |
| **EMR$_i$** | Exosomatic Metabolic Rate | ET$_i$/HA: amount of energy carrier *i* metabolized per hour of work allocated to end-uses | kWh/h or MJ/h |
| **EJP** | Economic Job Productivity | GVA/HA: value added per hour invested in end-uses | €/h |
| **EMD$_i$** | Exosomatic Metabolic Density | ET$_i$/US: amount of energy carrier *i* metabolized per quantity of area devoted to end-uses | kWh/m$^2$ or MJ/m$^2$ |
| **EUSP** | Economic Useful Surfaces Productivity | GVA/US: value added per area of end-use | €/m$^2$ |
| **ET$_i$** | Exosomatic Throughput | Amount of exosomatic throughput metabolized in the form of energy carrier *i* (electricity, heat or fuel) by end-use. | kWh/year or MJ/year |
| **GVA** | Gross Value Added | Value of goods and services produced by end-uses | €/year |

The organization of the elements of the system is the following:

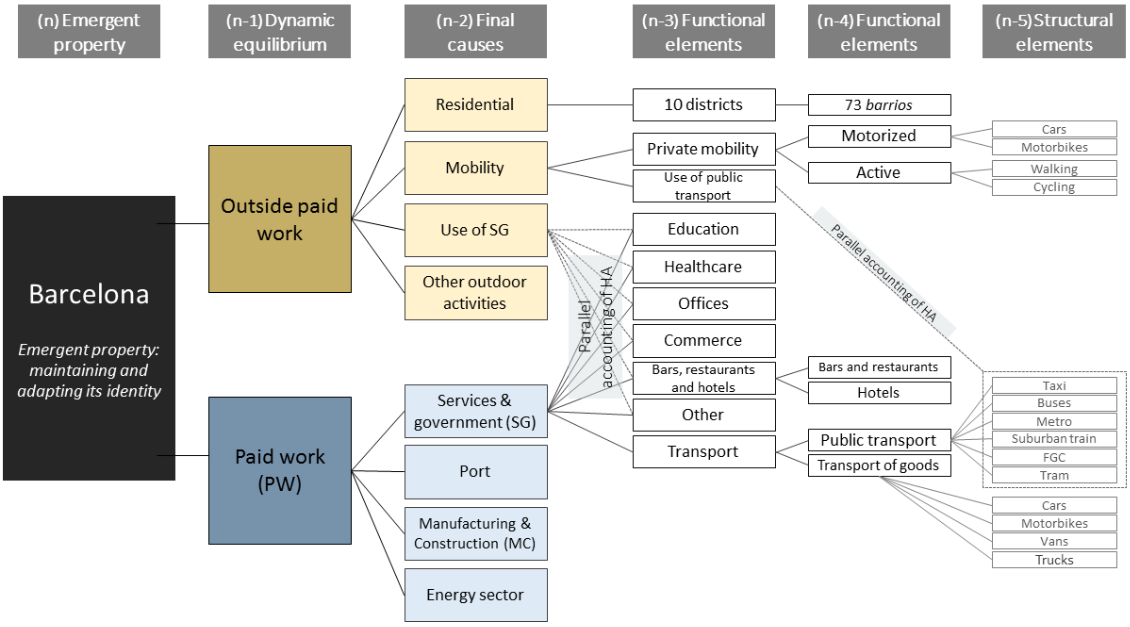
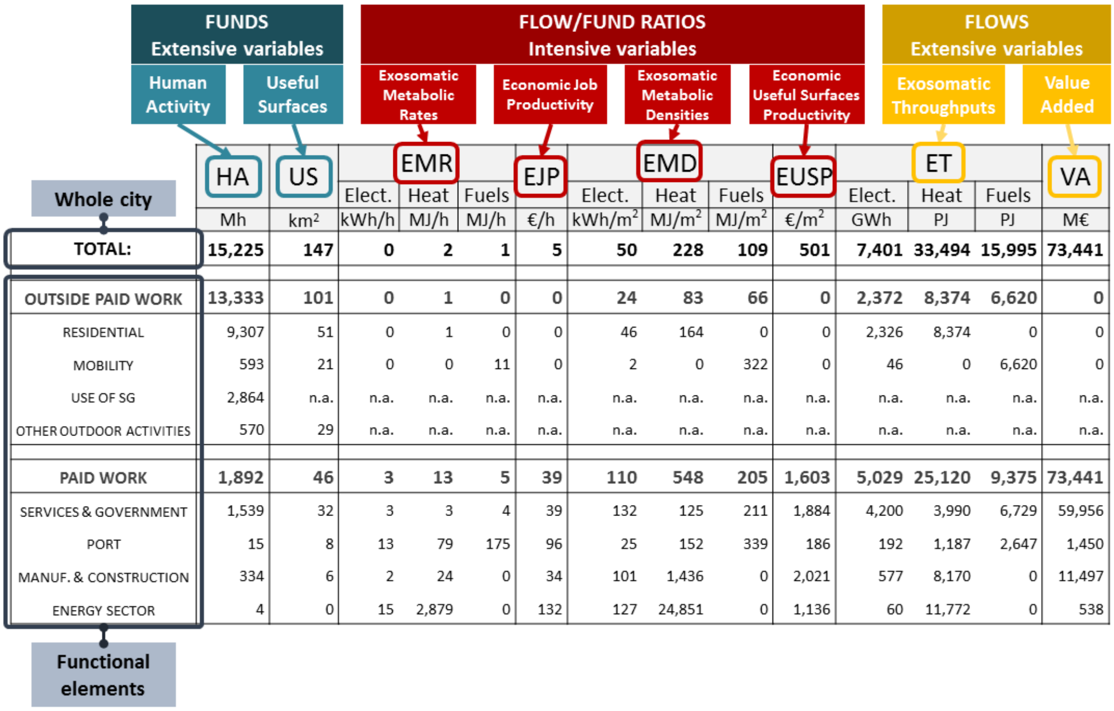


*Figure 4-7 Dendrogram of functional categories across levels of the Barcelona case study*



| | FUNDS Extensive variables | | FLOW/FUND RATIOS Intensive variables | | | | | | | | FLOWS Extensive variables | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Human Activity | Useful Surfaces | Exosomatic Metabolic Rates | | | Economic Job Productivity | Exosomatic Metabolic Densities | | | Economic Useful Surfaces Productivity | Exosomatic Throughputs | | | Value Added |
| Whole city | HA | US | EMR | | | EJP | EMD | | | EUSP | ET | | | VA |
| | | | Elect. | Heat | Fuels | | Elect. | Heat | Fuels | | Elect. | Heat | Fuels | |
| | Mh | km² | kWh/h | MJ/h | MJ/h | €/h | kWh/m² | MJ/m² | MJ/m² | €/m² | GWh | PJ | PJ | M€ |
| **TOTAL:** | **15,225** | **147** | **0** | **2** | **1** | **5** | **50** | **228** | **109** | **501** | **7,401** | **33,494** | **15,995** | **73,441** |
| **OUTSIDE PAID WORK** | **13,333** | **101** | **0** | **1** | **0** | **0** | **24** | **83** | **66** | **0** | **2,372** | **8,374** | **6,620** | **0** |
| RESIDENTIAL | 9,307 | 51 | 0 | 1 | 0 | 0 | 46 | 164 | 0 | 0 | 2,326 | 8,374 | 0 | 0 |
| MOBILITY | 593 | 21 | 0 | 0 | 11 | 0 | 2 | 0 | 322 | 0 | 46 | 0 | 6,620 | 0 |
| USE OF SG | 2,864 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| OTHER OUTDOOR ACTIVITIES | 570 | 29 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| **PAID WORK** | **1,892** | **46** | **3** | **13** | **5** | **39** | **110** | **548** | **205** | **1,603** | **5,029** | **25,120** | **9,375** | **73,441** |
| SERVICES & GOVERNMENT | 1,539 | 32 | 3 | 3 | 4 | 39 | 132 | 125 | 211 | 1,884 | 4,200 | 3,990 | 6,729 | 59,956 |
| PORT | 15 | 8 | 13 | 79 | 175 | 96 | 25 | 152 | 339 | 186 | 192 | 1,187 | 2,647 | 1,450 |
| MANUF. & CONSTRUCTION | 334 | 6 | 2 | 24 | 0 | 34 | 101 | 1,436 | 0 | 2,021 | 577 | 8,170 | 0 | 11,497 |
| ENERGY SECTOR | 4 | 0 | 15 | 2,879 | 0 | 132 | 127 | 24,851 | 0 | 1,136 | 60 | 11,772 | 0 | 538 |

*Figure 4-8 An overview of the end-use matrix of Barcelona. Numbers may not sum up due to rounding*

Considering this variables and organization of the system, the end-use matrix of the higher levels of analysis will be similar to the one in Figure 4-8.

In practice and when approaching the first overview of a system, extensive data from diverse sources are generally needed in order to fill the whole end-use matrix: energy throughput, value added, useful surfaces and human activity. Having these variables, the intensive variables can be calculated (top-down assessment). However, benchmarks of intensive variables from similar systems or elements can be used as well in order to find extensive variables (bottom-up estimation).

Generally, these data are reported and studied independently by specific disciplines, using different classifications, definitions and even units and elements of analysis. Moreover, they must be fitted as well to the defined organization of the system, avoiding double counting without losing relevant information of the system. For example, mobility can be explained by engineering looking at fuel consumption and power capacity of types of vehicles, whereas in geography the element of analysis is the person and their motivations to travel, with the main indicator would be the number of trips. Establishing relations over data gathered from an incoherent information space represents a major challenge, but also a great advantage of multi-dimensional and multi-scale analysis. Analysts must be careful in understanding the nature of the quantitative assessment they are using to filter-out the noise, avoiding double counting without losing relevant information and interpreting adequately the metadata of each indicator.

Other problems are the ones related to the limitation of the statistics to official and existing practices. For instance, assessments of work hours in shadow or informal economy are not included in labor statistics, yet very relevant. It explains the energy consumption that is effectively registered and the ability of some households to have an income. Thus, strategies must be found to include this time invested and value added generated. On the other hand, new work practices blur the boundaries of the elements. For example, there are statistics on taxis, but there aren’t on the sprouting trends that perform the same function linked with digital economy, like Uber or Cabify. Similarly, the impact of homeworking is unknown and it tears the established and clear boundary of residences and offices down. The lack of data could be only a problem of the novelty of these practices, and so, a question of time to overcome. However, it still challenges the organization of the elements of the system.

Problems may also arise when statistics are presenting data at a much aggregated level, or when only part of the set of variables are available. In the case of Barcelona, the port would be an example. It is a large infrastructure that includes activities from the three sectors of the economy (primary, secondary and tertiary). However, it has a clear function related to the transport of goods and people, allowing the externalization of functions to the industry and primary sectors of other societies. For this reason, it is interesting to assess its metabolic pattern as a separated element. In relation to this task, we can use assessments of its structural elements based on technical characteristics taken from literature. Then, if we include this analysis in the overall metabolic pattern, we have to subtract the values of the port from the values that include the port in other elements in order to avoid double counting.

This is to say, several assumptions had to be made in this case study. It is important to consider that the unavailability of information is not a problem to adopt the methodology that we present. It simply indicates that new information has to be gathered using more categories at different levels to be able to analyze the metabolism of the city.

Given all these difficulties found, most of the data have required the integration of diverse sources and assumptions. In**Error! Reference source not found.** Table 4-5, the 20 different calculation strategies referenced with letters can be seen. Some of the calculations, even though related to different elements, have the same sources and logic of data, and so, they share the reference. For example, the elements related to mobility (private mobility and public transport) belong to different functional compartments, but they share references of calculation. A general overview of the main data used is explained and listed ordered by variables in the following sections, human activity, building use, energy throughput and value added. For the exhaustive description of the calculations, see *APPENDIX 1. Detailed explanation of data processing*

(Lead author Laura Pérez-Sánchez). In Table 4-5 the different calculation strategies referenced with letters can be seen.

*Table 4-5 End-use matrix referencing the different approaches to calculate the variables.*

| | | | HA | US | ET | GVA |
|---|---|---|---|---|---|---|
| | | | h | m² | GJ or kWh | € |
| OUTSIDE PAID WORK | **RESIDENTIAL** | | | | | |
| | | 73 barrios | A | K | P | - |
| | **MOBILITY** | | | | | |
| | | Private motorized | B | L | Q | - |
| | | Active | C | | | |
| | | Taxi | B | - | | |
| | | Collective public transp. | D | | | |
| | **USE OF SG** | | | | | |
| | | Education | E | - | - | - |
| | | Healthcare | F | | | |
| | | Offices | | | | |
| | | Commerce | | | | |
| | | Hotels | | | | |
| | | Bars and restaurants | | | | |
| | | Other | | | | |
| | **OTHER OUTDOOR ACTIVITIES** | | G | L | - | - |
| PAID WORK | **SERVICES & GOVERNMENT** | | | | | |
| | | Education | H | M | R | V |
| | | Healthcare | | | | |
| | | Offices | | | | |
| | | Commerce | | | | |
| | | Hotels, bars and restaurants | | | | |

| | | | | |
|---|---|---|---|---|
| Other | | | | |
| Taxi | B | n.a. | Q | n.a. |
| Collective public transp. | I | | | |
| Transport of goods | B | K | | |
| **PORT** | J | N | S | W |
| **MANUFACT. & CONSTRUCT.** | H | M | T | V |
| **ENERGY SECTOR** | | O | U | |

### 4.2.2 Assessing quantities of Human Activity

The general logic for the accounting of human activity is to allocate in each function the time spent during the whole year. Due to the openness of urban systems, people spending their HA will continuously enter and exit, on a daily basis for work or other activities or for longer periods like holidays. A static certain amount of people cannot be defined to "be the city": 365 days/year · 24 h/day·#inhabitants doesn't work as the THA as it used to do at a national level, for instance. Thus, total human activity in the city will be calculated by summing all human activities associated with end-uses inside the administrative borders of the city.

#### *Identifying constituent components*

First it is necessary to identify the actors that decide to perform the activities in the city, what we call the constituent components. Not only residents are spending time in the city, and so, often, the calculation involves the sum of the time spent by the different actors, what we call constituent components: residents, commuters and tourists. The constituent components of a system are the essential parts that have to be reproduced in time and define its identity (see more about this in section 3). In the case of Barcelona, we abandon the traditional assumption that a city is associated only with its residents and introduce an approach including also other key agents:

- Residents: people who live in the city and are officially registered. They perform activities both inside and outside the city, but the only accounted will be those inside the city.
- Commuters: people who live in other municipalities of the AMB, but perform daily activities in Barcelona: shopping, studying, working, leisure, etc. They are key in providing work force required by the city.
- Tourists: people who visit the city from further regions. They can overnight or be only visitors for the day and they have 2 main reasons for their visit: leisure and Paid Work (e.g. participants of a congress). However, the human activity of tourists using congress spaces, hotels, restaurants, transport, etc. is not included in the activity of Paid Work of Barcelona, as they are registered as workers elsewhere, where they are being paid and generating value added. Tourists play a key role in providing demand to the service sector from the consumption side and therefore their human activity will be accounted in the use of services.

*Figure 4-9 Origin of the different constituent components of HA in the city of Barcelona: residents, commuters and tourists. Barcelona in blue, the rest of the metropolitan area in orange. Edited from AMB (http://www.30virtual.net/Noticias/8101)*

The main difference between constituent components is their geographical relation to the city, and all of them carry out activities outside of the system of analysis, but this time does not refer to the direct energy consumption of the city. Since we defined the system by the administrative boundary and we only account the activities happening inside, there is time of residents that is spent outside the city that is not included in the end-use matrix. If we wanted to do an analysis of the whole metropolitan area, we could sum the end-use matrixes of the different municipalities without double counting.

### *Assessing the end-use of human activity*

As discussed in Section 3, it is important to make a distinction between two kinds of end-use of human activity taking place in a city in order to stabilize its economy: the activity of workers and of consumers. This is translated into a parallel accounting of: (i) hours of human activity in Paid Work producing and making available the goods and services consumed in the city, (ii) hours of human activity outside PW consuming goods and services. Without taking this consumption into account, there would be no closure of the total time spent in the city: time at school, bars, shopping, etc. It would even leave invisible actors, e.g. tourists. This fact is especially relevant since Barcelona and a great amount of other cities are devoted mainly to services. It should be noted, that this analysis based only on the definition of work as paid work leaves out an important contribution of unpaid work which is essential to the expression of the metabolic pattern: cooking at home, people taking care of children, etc. This additional accounting fits perfectly into the proposed system of accounting, it just requires the addition of a new category of accounting to refine the original analysis inside the residential sector (not done here).

Even though different constituent components are taking part in the metabolism of the city, sometimes they are not all included in the same source of data. Because of this, after having identified the constituent components and their role in their in the metabolic pattern, it is essential to identify diverse sources of data and triangulate them. For example, mobility or time use surveys may refer only to the behavior of residents, therefore it is important to integrate this information with an analogous information referring to commuters and tourists.

In a touristic city like Barcelona there is a considerable amount of research done on tourists, whereas the same attention has not be given to the analysis of the impact that residents of the metropolitan area (commuters) have on commerce and leisure activities in Barcelona. In this study the data on human activity for leisure and shopping activities of commuters in Barcelona are based on several assumptions, and are not as robust as the others. Moreover, the differences between actors considered the same constituent component might be relevant but difficult to characterize. For instance, the use of time of a person will vary depending on the period of their life, their inclusion or not in the paid work system, gender, nationality, etc. In the case of Barcelona, human activity for residents has been calculated by age groups. For tourists a double assessment was made with overnight/visitor and motivation to travel (leisure, professional and personal and other). For commuters there was not enough information available to define robust typologies.

In general terms the characteristics of categories of human activity are difficult to define and are not captured by statistics. For example, there is not a proper accounting of the increasingly large number of temporary residents that have hybrid behaviors between tourists and residents (Martínez *et al.*, 2014). Moreover, one of the most important problems found when using statistics is the shadow economy. It is not properly represented in official work statistics, but it is relevant in terms of the metabolism of the city. To make things worse, the energy consumption of activities carried out in the shadow economy is accounted in the statistics. This extra human activity doing work but not registered in official statistics was included in the accounting through estimation – details are given in *APPENDIX 1. Detailed explanation of data processing*

(Lead author Laura Pérez-Sánchez).

*Table 4-6 Main data used in the calculation of human activity in the analysis of Barcelona*

| HUMAN ACTIVITY | | | [h] | Main data used |
|---|---|---|---|---|
| OUTSIDE PAID | RESIDENTIAL | | | |
| | | 73 barrios | A | Hours per day of the activities happening inside the households from the survey of use of time in Catalunya (IDESCAT, 2012a).<br>Hypothesis of share of time happening inside households.<br>Number of inhabitants per age group per *barrio* (Ajuntament de Barcelona, 2012a).<br>Holiday days outside of the city (Observatori d'Empresa i Ocupació, 2012). |
| | MOBILITY | | | |

| | | | | |
|---|---|---|---|---|
| | | Private motorized | B | km run per kind of vehicle in Barcelona (provided by Agència de l'Energia -AEB)<br>Average occupancy of the vehicles (Ajuntament de Barcelona, 2011).<br>Share allocated to each category (transport of goods, taxi, private mobility).<br>Average speed (Ajuntament de Barcelona, 2013). |
| | | Active | C | Number of trips of locals and tourists (Ajuntament de Barcelona, 2013)<br>Average distance (Ajuntament de Barcelona, 2011).<br>Average speed (Ajuntament de Barcelona, 2013). |
| | | Collective public transport | D | Number of trips of riders (Ajuntament de Barcelona, 2013).<br>Average distance in the city (Ajuntament de Barcelona, 2011).<br>Average speed (Ajuntament de Barcelona, 2013) |
| | | Taxi | B | km run per kind of vehicle in Barcelona (Ajuntament de Barcelona, 2013).<br>Average occupancy of the vehicles (Ajuntament de Barcelona, 2013).<br>Share allocated to each category (transport of goods, taxi, private mobility).<br>Average speed (Ajuntament de Barcelona, 2013). |
| | USE OF SG | | | |
| | | Education | E | Number of students in the city per level (Ajuntament de Barcelona, 2012a).<br>Number of hours of study per year, based on regulations and hypothesis. |
| | | Healthcare<br>Offices<br>Commerce<br>Hotels<br>Restaurants<br>Other | F | Residents and commuters: survey of use of time (IDESCAT, 2012a), reports on share of consumption inside the city/out (Ajuntament de Barcelona, 2012b; IDESCAT *et al.*, 2012), holiday days outside of the city (Observatori d'Empresa i Ocupació, 2012).<br>Tourists: number of tourists, number of days of stay per tourist (Direcció de Serveis de Mobilitat and Direcció Operativa de Turisme i Esdeveniments, 2014) hypothesis. |
| | OTHER OUTDOOR ACT. | | G | Residents: Hours per day of the activities happening at streets from the survey of use of time in Catalunya (IDESCAT, 2012a).<br>Hypothesis of share of time happening inside households.<br>Number of inhabitants per age group per barrio (Ajuntament de Barcelona, 2012a).<br>Holiday days outside of the city (Observatori d'Empresa i Ocupació, 2012)<br>Commuters:<br>Number of trips to Barcelona with Other outdoor activities motivation (IERMB, 2013)<br>Tourists: number of tourists, number of days of stay per tourist (Direcció de Serveis de Mobilitat and Direcció Operativa de Turisme i Esdeveniments, 2014) hypothesis |
| | | | | |
| PAID WORK | SERVICES & GOVERN. | | | |
| | | Work<br>Education<br>Healthcare<br>Offices<br>Commerce<br>Hotels, bars&rest.<br>Other | D | Number of workers per sub-sector (Ajuntament de Barcelona, 2012a)<br>Number of hours of work per year per sector (IDESCAT, 2012b), including only working days.<br>Assessment of shadow economy. |
| | | Collective public transport | H | Number of workers in the companies of public transport (IERMB, 2012b; Transports Metropolitans de Barcelona, 2012; Renfe, 2014).<br>Number of hours of work in the service sector (IDESCAT, 2012b)<br>Share of km inside the city (provided by AEB). |
| | | Taxi<br>Transport of goods | B | km run per kind of vehicle in Barcelona (provided by AEB).(Ajuntament de Barcelona, 2013)<br>Average occupancy of the vehicles (Ajuntament de Barcelona, 2013)<br>Share allocated to each category (transport of goods, taxi, private mobility).<br>Average speed (Ajuntament de Barcelona, 2013) |

| | | | |
|---|---|---|---|
| | PORT | I | Number of workers (Port de Barcelona, 2012).<br>Number of hours of work per year per sector (IDESCAT, 2012b), including only working days. |
| | MANUF. & CONSTR. | D | Number of workers per sub-sector (Ajuntament de Barcelona, 2012a)<br>Number of hours of work per year per sector (IDESCAT, 2012b), including only working days..<br>Assessment of shadow economy. |
| | ENERGY SECTOR | | |

### *Assessing the sources of human activity*

Having all end-uses with their HA, a calculation can be made to analyze the weight of the different constituent components. The budget of human time of the city is dynamic, not only due to the demographic variation of the residents, but also to the contribution of commuters in the market economy and the additional consumption of services by tourists. The relationship between constituent components and functional elements can be seen in Figure 4-10. In that figure, it is also included the quantity of time that residents spend outside the city even though it is not accounted in the end-use matrix. The main strategies used to assess the human activity spent by each constituent component are shortly explained in Table 4-7.

Sometimes the distinction was directly a condition of the calculation of the end-uses, i.e. the HA for an end use was the sum of HA of the three constituent components, and so no further calculations were needed. In general, the distinction of the HA of constituent components was made at a low level of analysis. However, in the case of Paid Work, it could only be made at the highest level (n-1), with aggregated data.

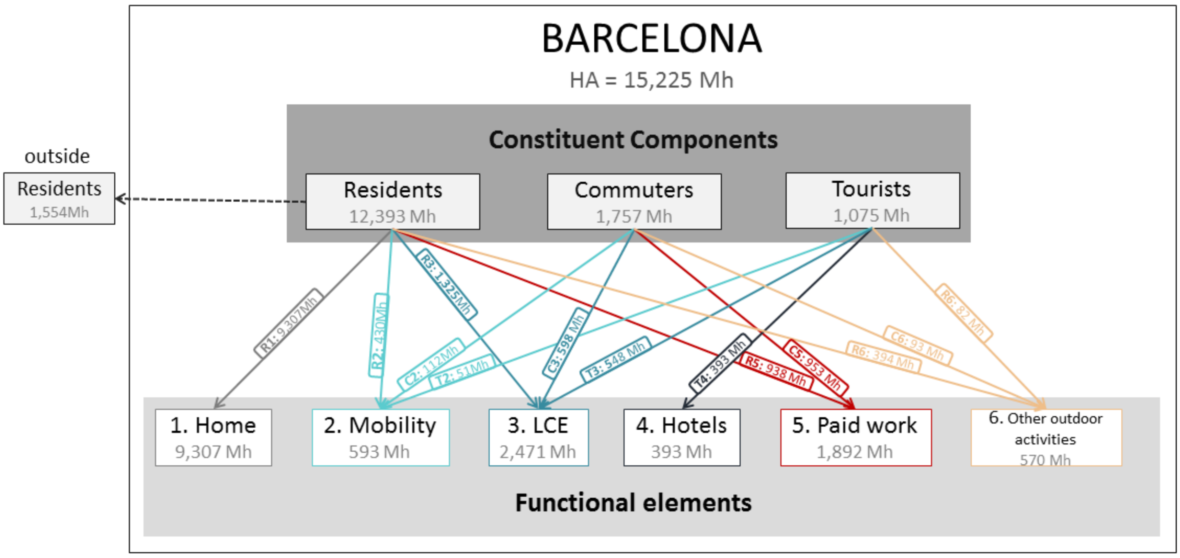


*Figure 4-10 Classification and relationship of human activities per constituent component and functional elements*

*Table 4-7 Calculations of the disaggregation of the time in functional elements by constituent components*

| Functional element | Related HA calc. | Constituent component | Allocation strategy |
|---|---|---|---|
| **1. Home** | (A) | R1: Residents | All time in residential |

| | | | |
|---|---|---|---|
| **2. Mobility** | (B), (C), (D) | R2: Residents<br>C2: Commuters | Hypothesis: share of time of residents and commuters is the same as share of trips: 79.3% of the trips are of residents (IERMB, 2012a) |
| | | T2: Tourists | Calculation of HA from the share of trips of tourists (Ajuntament de Barcelona and Barcelona Regional, 2017). |
| **3. LCE** | | R3, C3, T3 | |
| Education | (E) | Residents<br>Commuters | Share of students in Barcelona by place of residence (Ajuntament de Barcelona, 2012a) |
| Healthcare, offices, commerce, Bars and restaurants and other | (F) | Residents, commuters, tourists | Already accounted separately in (F) in Table 4.6 |
| **4. Hotels** | (F) | T4: Tourists | All time in the consumption side of hotels |
| **5. Paid Work** | (B), (H), (I), (J) | R5: Residents<br>C5: Commuters | Amount of human activity in Paid Work.<br>% of workers in Barcelona by place of residence (Ajuntament de Barcelona, 2012a) |
| **6. Other outdoor activities** | (G) | R6: Residents<br>C6: Commuters<br>T6: Tourists | Already accounted separately in (G) in Table 4.6 |

### 4.2.3 Assessing quantities of areas used (Built Environment)

As we have already defined, the boundary chosen for this study is the administrative domain of the city; the study refers to the activities taking place in it during the year 2012. There are many ways to account the area. As explained in Section 3 we use four distinct accounting categories for measuring areas:

- Useful Surfaces associated with end uses: it is the sum of Building Use (e.g. area of flats inside buildings in all the floors for Residential and services) and Land Use (e.g. road network for Mobility). It is accounted in the End-use matrix in the MuSIASEM framework;
- Building Use (BU): internal floor area, referring to the internal area in use in buildings.
- Land Use (LU): area of the city occupied by a building or to which it has been assigned a function (e.g. roads, urban parks). The choice of categories must provide closure: the sum of all the land uses gives the area occupied by the city (TLU). A source of this data could be urbanism plans.
- Area of the administrative unit (*barrio*, district, city). The sum gives the area occupied by the city (TLU). These are the constituent components of the city.

*Figure 4-11 A building located in one certain land use might have more than one level and devote them to different activities, multiplying the available area*

*Figure 4-12 Part of a map of Barcelona showing the different land uses*

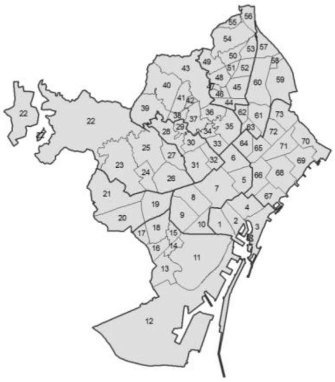


*Figure 4-13 The 73 barrios of Barcelona: the spatial constituent components*

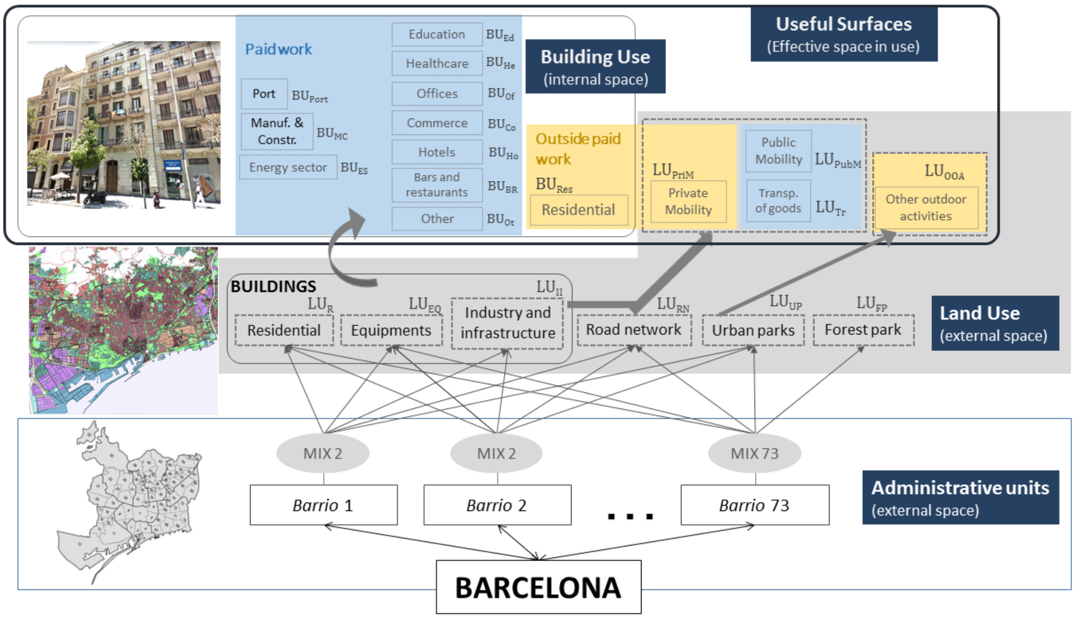


*Figure 4-14 Classification and relationship of spatial elements per constituent component and functional elements*

Although the administrative limits of the city do not vary, the Useful Surface of the city might increase due to the construction of more or taller buildings: depending on the activity of the construction sector. This may imply a difference between a 2D definition of area ($LU_i$) and the useful surface used inside the buildings (reflecting changes in 3D) depending on the number of storeys ($BU_i$). The difference between $BU_i$ and $LU_i$ depends on the mix of Land Uses (the density of buildings) and the height of the buildings. This difference is assumed to remain constant during the time span of the analysis. Normally, administrations register all real state classified by categories in the cadaster, being this the main source of data for this variable.

*Table 4-8 Main data used in the calculation of useful surface in the analysis of Barcelona*

| USEFUL SURFACES | | | [$m^2$] | Main data used |
|---|---|---|---|---|
| OUTSIDE PAID WORK | RESIDENTIAL | | | |
| | | 73 barrios | J | BU: Opendata BCN (Ajuntament de Barcelona, 2016b) |
| | MOBILITY | | | |
| | | Private motorized | K | LU: Share of area of streets occupied by each mode of transport (pedestrians or vehicles) (Ajuntament de Barcelona, 2013) |
| | | Active | | |
| | OTHER OUTDOOR ACTIVITIES | | L | LU of parks, beaches, etc. (Ajuntament de Barcelona, 2012a) |
| | | | | |
| PAID WORK | SERVICES & GOVERNMENT | | | |
| | | Education | M | BU: AEB or Opendata (Ajuntament de Barcelona, 2016b) |
| | | Healthcare | | |
| | | Offices | | |
| | | Commerce | | |
| | | Hotels, bars&restaurants | | |
| | | Other | | |
| | | Collective pub. transp. | - | No data could be found. |
| | | Taxi | - | - |
| | | Transport of goods | K | LU: Share of area of streets that are dedicated to vehicles (Ajuntament de Barcelona, 2013) |
| | PORT | | N | LU: Report of the Agència Portuaria (Port de Barcelona, 2018) |
| | MANUF. & CONSTR. | | M | BU direct from Opendata web service (Ajuntament de Barcelona, 2016b) |
| | ENERGY SECTOR | | O | LU: Agència Portuaria GIS website (Port de Barcelona, 2018) |

Buildings are durable infrastructure which shapes the possible uses. For example, equipment like schools or sport centers are designed according to their final educational or sport use. These designs and land uses can be further regulated in local normative and urbanism plans. And so, structural changes can only be made mid/long-term and depend on political plans. Being land a scarce resource, it is potentially affected by price increases. This fact can expel from the city some activities or residents. It is also possible that registers and statistics are not updated at the speed of change of these activities, or that these classifications do not define clearly the function. For example, the term religious could include not only places of worship (churches, mosques, temples, etc.) but also schools, hospitals, etc.

On a lower level, the required space is defined by a combination of the characteristics of the activity (functions, scale, specialization, variety of products, scale of the production, comfort of the workers and users, etc.); and its technical aspects (size of machinery, existence of warehouses or logistic areas, size of the customer area, etc.). In residential sector, area is an indicator of the comfort that a household unit wants to have or is able to afford, and so, of their material standard of living. Also, specific dwellings could be used by temporary residents or tourists, and so we can have the same structural type expressing different functions.

### 4.2.4 Assessing quantities of Energy Throughputs

As already explained, we define a classification of energy carriers in three distinct categories: electricity, heat and fuels, following the guidelines described by Velasco-Fernández (2017) and Velasco-Fernández et al. (2018). However, statistics and reports usually only include aggregated values of EC, for this reason, one of the main challenges is to disaggregate this data into the in the three categories of EC for which we can define difference in the quality of 1 MJ. At a technical level, this qualitative distinction of energy is key. To do this, sectorial reports on energy efficiency are available, for example: shopping centers or heating systems in administrative buildings. For example, *Propostes per a la Rehabilitació Energètica d'habitatges a Barcelona. Estudi tècnic PECQ 2011-2020* (Agència d'Energia de Barcelona, 2011) had information on energy consumption in buildings, where the energy carrier consumptions (gas, electricity, GLP, solar and others) are disaggregated by type of end-uses (heating, cooling, domestic hot water, illumination, equipment and others). However, these examples are not the general rule, the great amount of data on power capacity, energy consumption per carrier and function collected for energy efficiency improvements is not available in many cases, since final indicators are aggregated (Farreny *et al.*, 2012; Ministerio de Fomento, 2014).

In the case of Barcelona, most of the data comes at a functional element level with general benchmarks and data, only in the case of mobility and transport the calculation was made at a structural element. One of the interesting approaches to do in the future would be to open these black boxes and analyze the structural elements that are carrying out the diverse functions, since they can have a great diversity. In the case of residential sector, data is available by barrio. Each barrio is quite homogeneous in terms of building types and socio-economic aspects, but different from each other. This makes it possible to analyze the differences in energy consumption across barrios in relation to the differences in the characteristics of their building types and socio-economic aspects.

*Table 4-9 Main data used in the calculation of energy throughput in the analysis of Barcelona*

| EXOSOMATIC THROUGHPUT | | | [kWh or GJ] | Main data used |
|---|---|---|---|---|
| OUTSIDE PAID WORK | RESIDENTIAL | | | |
| | | 73 barrios | P | Total energy consumption (aggregated) per *barrio*, 2012 (provided by Agència de l'Energia -AEB).<br>Divided by electricity and heat (explanation in the Appendix). |
| | MOBILITY | | | |
| | | Private motorized | Q | km run by type of vehicle in 2013 (provided by AEB).<br>Fuel or electricity used per km (provided by AEB).<br>Share allocated to each category (transport of goods, taxi, private mob), hypothesis constructed from different statistics.<br><br>Lightning (Observatori de l'Energia de Barcelona, 2013) |
| | | Active | | |
| | | Collective pub. transp. | | |
| | | Taxi | | |
| | | | | |
| PA | SERVICES & GOVERNM. | | | |

| | | | | |
|---|---|---|---|---|
| | | Education | R | Education and healthcare:<br>PECQ 2011-2020 (Ajuntament de Barcelona, 2011)<br>Offices, commerce, hotels, restaurants:<br>Aggregated (electricity + heat) energy consumption (provided by AEB). Share of thermal energy and electricity in different sectorial reports (INDESCAT, 2012; Gauchia Legal, 2013; Nuñez-Cacho del Águila, 2013; PyME Energy CheckUp, 2013, 2014, 2015)<br>Other:<br>Agència data for the whole sector (closure of bottom-up from the other elements, the general consumption of the service sector (provided by AEB)) |
| | | Healthcare | | |
| | | Offices | | |
| | | Commerce | | |
| | | Hotels, bars&rest. | | |
| | | Other | | |
| | | Collective pub. transp. | Q | km run by type of vehicle in 2013 (provided by AEB).<br>Fuel or electricity used per km (provided by AEB).<br>Share allocated to each category (transport of goods, taxi, private mob), hypothesis constructed from different statistics.<br>Lightning (Observatori de l'Energia de Barcelona, 2013) |
| | | Taxi | | |
| | | Transport of goods | | |
| | PORT | | S | Energy and GHG emissions of the port of Barcelona (Villalba and Gemechu, 2011) |
| | MANUF. & CONSTR. | | T | Provided by ICAEN |
| | ENERGY SECTOR | | U | Deliverable 4.1 for the MAGIC-Nexus project (Di Felice, Ripa and Giampietro, 2017) |

### 4.2.5 Assessing quantities of Gross Value Added

Gross Value Added (GVA) is a measure of the monetary flows produced by the compartments. An assessment of shadow economy has been done.

The elements in Outside Paid Work are characterized by not generating VA. This doesn't imply that they are not important for the economy, but that they are not recognized or accounted in the formal market. This is the case of many of the caring work developed mostly by women in households and that is essential for the economy.

*Table 4-10 Main data used in the calculation of value added in the analysis of Barcelona*

| GROSS VALUE ADDED | | | [€] | Main data used |
|---|---|---|---|---|
| OUTSIDE PAID WORK | RESIDENTIAL | | - | No value added by definition. |
| | MOBILITY | | | |
| | OTHER OUTDOOR ACTIVITIES | | | |
| | | | | |
| PAID WORK | SERVICES & GOV. | | | |
| | | Education | V | Value added per sub-sector from city council statistical website (Ajuntament de Barcelona, 2012a).<br>Assessment of shadow economy. |
| | | Healthcare | | |
| | | Offices | | |
| | | Commerce | | |
| | | Hotels | | |
| | | Restaurants | | |
| | | Other | | |
| | | Collective pub. transp. | - | Data at this level couldn't be found. However, all the sector is included at the n-4 level - Transport (Ajuntament de Barcelona, 2012a). |
| | | Taxi | | |

| | | | | |
|---|---|---|---|---|
| | | Transport of goods | - | The value added generated might be associated to companies located in other places. |
| | PORT | | W | Agència Portuaria report (Port de Barcelona, 2012). |
| | MANUF. & CONSTR. | | V | Value added per sub-sector from city council statistical website (Ajuntament de Barcelona, 2012a).<br>Assessment of shadow economy. |
| | ENERGY SECTOR | | | |

## 4.3 Examples of quantitative results: the End-use matrix

### 4.3.1 Introduction

As already explained, the quantitative assessments presented below should be considered as preliminary results with the goal of testing the possibility of describing the metabolic pattern of a city using the MuSIASEM approach. The long theoretical discussions in Section 3 and practical discussions in Section 4 and Appendix 1 about the challenges of this approach show that this type of exercise should be carried out:

(i) in a participatory way – by co-producing the results together with the users of the relational analysis when deciding the issues to be addressed, categories of the functional and structural elements, and the data selection;
(ii) by a diverse pool of experts in order to guarantee the robustness of the results;
(iii) in an iterative way – by starting with a preliminary set of results, where the numbers included in the multilevel end-use matrix should be considered as place-holders waiting for successive more robust assessments.

These three requirements were only partially fulfilled in the process of generation of the results presented below. This study started in 2016 and during its preparation we had a few contacts with the local administration of Barcelona, more specifically: Agència de l'Energia de Barcelona, Barcelona Regional and Port de Barcelona. Due to the exploratory nature of our study and the workload of the experts in the public administration, it was not possible to have a long and continuous discussion on the details of our calculations. In relation to the involvement of a heterogeneous pool of experts, we tried to contact as many as possible to gather both insights and data. However, we realized soon that a systemic identification of all the required experts and the establishment of an effective process of interaction with them was not compatible with the exploratory nature of this exercise. Likewise, involving other social actors was not compatible with the budget of the study. For all these reasons the requirement of co-production was not fulfilled. Finally, the same building process of the new methodology and the progressive finding of new data forced a few iterations on the identity of the end use matrix, but this was made inside our group. That is, after looking at the first round of results we had an internal process of learning how to do it better, decided to redefine the categories of accounting and to redistribute the funds and flows among functional and structural elements.

### 4.3.2 General overview of the system

In Table 4-1, one can see the end-use matrix of the higher levels of analysis of the Barcelona case study. The end use matrix can be used to establish a quantitative link across different levels of analysis. In this case three different levels of analysis are shown:

(i) level n, the whole Barcelona – in the row labelled as TOTAL;

(ii) level n-1, where the total is split in two main functional categories: *outside paid work* and *paid work*;

(iii) level n-2, where each of the two categories is split into lower level categories: "Outside Paid Work" in Residential, Mobility, Use of Services and Government, and Other Outdoor Activities; and "Paid Work" into Services and Government, Port, Manufacturing and Construction and Energy Sector.

*Table 4-11 End-use Matrix (levels n/n-1/n-2) describing the metabolic pattern of Barcelona with the variables HA, $ET_i$, GVA and their metabolic ratios $EMR_i$ and EJP*

| | HA | EMR | | | EJP | ET | | | VA |
|---|---|---|---|---|---|---|---|---|---|
| | | Elect. | Heat | Fuels | | Elect. | Heat | Fuels | |
| | Mh | kWh/h | MJ/h | MJ/h | €/h | GWh | TJ | TJ | M€ |
| **TOTAL:** | **15,225** | **0.5** | **2.2** | **1.0** | **5** | **7,401** | **33,914** | **15,576** | **73,441** |
| **OUTSIDE PAID WORK** | **13,333** | **0.2** | **0.6** | **0.5** | **0** | **2,372** | **8,374** | **6,620** | **0** |
| RESIDENTIAL | 9,307 | 0.2 | 0.9 | 0.0 | 0 | 2,326 | 8,374 | 0 | 0 |
| MOBILITY | 593 | 0.1 | 0.0 | 11.2 | 0 | 46 | 0 | 6,620 | 0 |
| USE OF SG | 2,864 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| OTHER OUTDOOR ACTIVITIES | 570 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| **PAID WORK** | **1,892** | **2.7** | **13.5** | **4.7** | **39** | **5,029** | **25,539** | **9,375** | **73,441** |
| SERVICES & GOVERNMENT | 1,539 | 2.7 | 2.9 | 4.1 | 39 | 4,200 | 4,410 | 6,309 | 59,956 |
| PORT | 15 | 12.7 | 78.5 | 175.1 | 96 | 192 | 1,187 | 2,647 | 1,450 |
| MANUFACTURING & CONST. | 334 | 1.7 | 24.5 | 0.0 | 34 | 577 | 8,170 | 0 | 11,497 |
| ENERGY SECTOR | 4 | 14.7 | 2,879.2 | 0.0 | 132 | 60 | 11,772 | 0 | 538 |

When determining the dynamic equilibrium between the Bioeconomic Pressure (BEP) and the Strength of the Exosomatic Hypercycle (SHE) of a system (Giampietro et al. 2012) Outside paid work and Services and Government are considered as net consumers of biophysical flows (dissipative sectors), which must be supplied by the primary and secondary sectors (productive sectors: Energy and Mining, Agriculture, and Manufacturing and Construction). In fact, the largest share of HA of paid work in Barcelona is allocated to the SG sector, which presents larger $EMR_{el}$ compared to MC and makes SG the higher $ET_{el}$ consumer. In the case of heat, SG has the lower EMR, and despite the large share of HA in SG, ES and MC are largest $ET_{heat}$ consumers. However, when comparing the EMRs of Barcelona in the Manufacturing and Construction sector ($EMR_{el}$ =

2 kWh/h, $EMR_{heat}$ = 25 MJ/h, $EMR_{fuel}$ = 0 MJ/h) with the average of Europe ($EMR_{el}$ = 16 kWh/h, $EMR_{heat}$ = 103 MJ/h, $EMR_{fuel}$ = 7.1 MJ/h) (Giampietro, Sorman and Velasco-Fernández, 2017; Velasco-Fernández, 2017) and the distribution of HA inside MC, we can see that the larger MC subsectors in Barcelona are rather non energy-intensive: construction sector, which has the lowest EMRs in the MC sector, and manufacturing of vehicles, in this case assembling. These sectors will be further analyzed hereafter.

Besides this traditional classification of economic sub-sectors, in the case of Barcelona there's the port, which shows high EMRs and EJP. These values can be explained by the use of large machinery and ships, and the low amount of work. The relevance of this infrastructure for the city of Barcelona is difficult to assess both in monetary terms and biophysical terms since it carries out international shipping both for exports and imports of energy, food and products, providing services to a larger area that cannot be assessed. The port is a node of an international network and a basic part of the Barcelona system, which allows the externalization of manufacturing, energy, mining and agriculture functions.

Moreover, the port has the largest power plant in Barcelona producing electricity, a combined cycle thermoelectric plant. This element is as well considered separately, in the Energy Sector functional element. When looking the energy self-sufficiency of Barcelona, we can make an easy estimation in relation to this power plant, since the other large power plants are out of the boundaries, and PV represents only about 0.2%. Considering that it consumes all the $ET_{heat}$ in the energy sector of Barcelona (11,800 PJ) and that it has an efficiency of 58%, the production of electricity in Barcelona in 2012 was 1,896 GWh, around the 25% of the electricity consumption of the city. Thus, it only provides part of the electricity consumed by the city, and it works as a peaker. Moreover, the energy carrier that makes it work, natural gas, is imported. As we can see, Barcelona presents an energy pattern typical of most cities: it is basically a dissipative system. As explained in Section 3, this is why any analysis of an urban system just focused on the activities inside the borders of the city would explain just part of the story. It would require an analysis in relation to its openness to have a complete metabolic explanation of its performance.

At this level of aggregation it is not possible to identify relevant differences in structural and functional elements. To do so, we characterize the elements at a lower level:

(i) on the role of services: the associated activities.
(ii) in the transport sector: private and public elements;
(iii) in the residential sector: different *barrios*;

By the sudoku-effect (Giampietro and Bukkens, 2015), we can open a row of the matrix (defined at the level n-2) and define it as the total of an end-use matrix describing its lower level components.

### 4.3.3 Services and government

In Table 4-12 the Services and Government sector with its immediate lower level elements end use matrix can be seen: education, healthcare, offices, commerce, hotels, bars and restaurants, other and transport. At this level we can analyze no longer in relation to a very generic definition of functional sector (SG), but in relation to more specific definitions of activities that are developed inside it.

*Table 4-12. End-use Matrix (level n-2/n-3) describing the metabolic pattern of the Services and Government sector of Barcelona*

| | HA | US | EMR | | | EJP | EMD | | | EUSP | ET | | | VA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Elect. | Heat | Fuel | | Elect. | Heat | Fuel | | Elect. | Heat | Fuel | |
| | Mh | km$^2$ | kWh/h | MJ/h | MJ/h | €/h | kWh/m$^2$ | MJ/m$^2$ | MJ/m$^2$ | €/m$^2$ | GWh | TJ | TJ | M€ |
| **SERV. & GOV.** | **1,539** | **31.8** | **2.7** | **2.9** | **4** | **39** | **132** | **139** | **198** | **1,884** | **4,200** | **4,410** | **6,309** | **59,956** |
| Education | 101 | 3.6 | 1.3 | 6.3 | 0 | 35 | 38 | 177 | 0 | 986 | 135 | 637 | 0 | 3,542 |
| Healthcare | 157 | 1.9 | 1.4 | 1.3 | 0 | 22 | 116 | 104 | 0 | 1,805 | 223 | 201 | 0 | 3,477 |
| Offices | 641 | 7.0 | 1.9 | 1.2 | 0 | 45 | 177 | 112 | 0 | 4,075 | 1,246 | 792 | 0 | 28,697 |
| Commerce | 321 | 8.3 | 4.1 | 5.4 | 0 | 35 | 156 | 208 | 0 | 1,337 | 1,300 | 1,730 | 0 | 11,114 |
| Hotels, bars, etc. | 135 | 2.0 | 2.2 | 2.0 | 0 | 37 | 149 | 133 | 0 | 2,467 | 304 | 270 | 0 | 5,031 |
| Other | 119 | 3.7 | 5.9 | 3.0 | 0 | 33 | 190 | 99 | 0 | 1,063 | 696 | 360 | 0 | 3,881 |
| Transport | 65 | 5.3 | 4.6 | 6.5 | 104 | 65 | 56 | 80 | 1,199 | 800 | 296 | 419 | 6,309 | 4,212 |

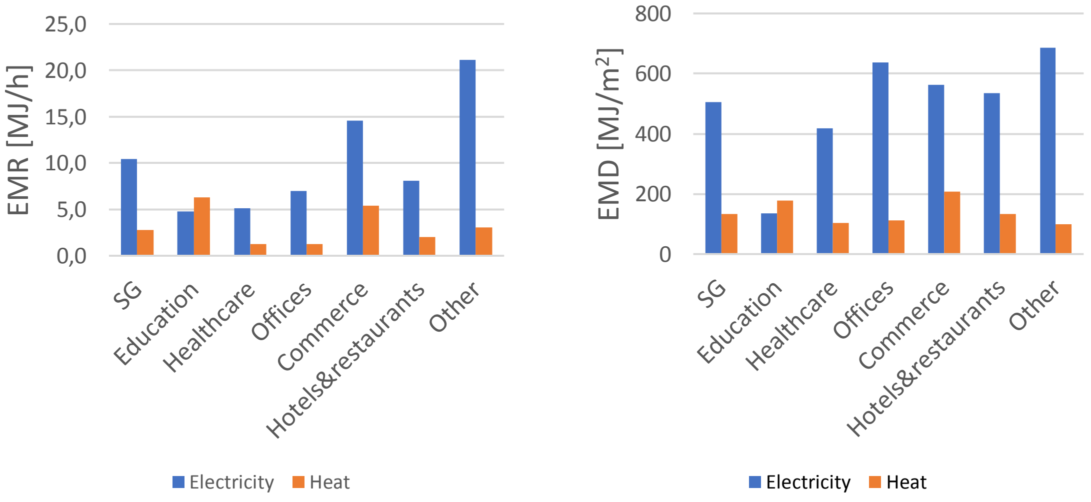


*Figure 4-15 Metabolic characteristics of functional elements inside Services and Government (n-4): EMR (flow per hour) and EMD (flow per m$^2$), without transport.*

Service and government, including both services to people and to companies, is the largest sector in Barcelona regarding ET$_{elec}$, ET$_{fuel}$, VA and HA. Inside it, Offices is its main subsector in terms of HA and VA, and still it has the highest EJP and EUSP. However, it has low EMR comparing to the other sub-sectors. Offices is also generally a desirable way to be employed in relation to social status, income and work conditions (AC, sitting down and no physical effort, low levels of noise). We can relate this with the international context where cities compete to be global cities, attracting yuppies and investment on IT, media and finance. Moreover, in the case of Barcelona this is still in process with a strategic plan of the city council: the 22@ area, formerly an industrial area. It is presented as "*a system of innovation- cutting edge companies, universities and training centres, and centres of research and transfer of technology*" (Ajuntament de Barcelona, 2018), with the final aim to make of Barcelona the "capital of innovation" (Europa Press, 2017). This creation of new buildings of offices, increasing the economic activity and attracting more workers to the city will increase the energy consumption no matter how efficient are the new infrastructures if there is no substitution of economic activities, but net increase. However, at a larger time scale, these service sectors are replacing industrial activity. These changes of economic activities are crucial to the energy consumption and emissions taking place in the city, which have nothing to do with the origin of the energy or the efficiency of the process. This becomes very relevant on how to account the decrease of 20% of GHG emissions in relation to the Baseline Emission Inventory in the Covenant of Mayors.

The category *Other* includes entertainment, arts, sports and other activities. It has to be analyzed carefully, since there is some part of these "Other" formed of "other" categories that weren't clarified by statistic offices. Moreover, this category was used to fit bottom-up data to top-down one.

### ***Exploring what's inside the functional elements: structural elements***

After having identified a specific combination of functional and structural elements we can finally generate specific assessments to be used for comparing. At this level we can compare the metabolic characteristics of "apples with apples and oranges with oranges". In the same way that industry and services are not comparable since they perform different functions, there are many ways to express Education or Commerce and they might not be comparable. Education, for example, can be resource intensive: done in small groups and so requiring a great amount of paid work HA; with lots of technical equipment consuming electricity; and be time extensive like university, with a great amount of user HA and delaying the entry into employment. On the other hand, education can also be done in big groups with basic equipment to provide basic education and introduce youngsters to paid work at an early age.

We couldn't address this level of detail in this study, but an idea of the structural elements at level n-5 for diverse compartments of Services and Government is shown in Table 4-13 to enable comparisons in future studies of other cities. In this example, we can see that after having individuated the structural elements required to observe to study metabolic characteristics, we combine information about:

(i) technological performance - coefficients defined per unitary operations (e.g. the emission per km transported of a technical solution);
(ii) relative size – a bad performance of a negligible process is not important, whereas a bad performance in a very spread-out process must be considered as a priority;
(iii) context– what is the final cause to which each function refers to, can we imagine different functional elements providing services in relation to the same final cause?

*Table 4-13 An analysis of structural elements associated with lower level functional elements in the Services and Government sector*

| **Functional element (n-3)** | **Structural elements (n-4)** |
|---|---|
| *Education* | *Non-university students: 240,000 students (early childhood 24%, elementary 33%, middle school 22%, high school 9%, vocational training 12%). University level: 190,000 students.* |
| *Healthcare* | *64,015 cases of illnesses, 10,987 flu cases*<br>*51 primary health care centers*<br>*43 hospitals with 7,889 beds: 353,802 hospital contacts (57,3% residents, 39% rest of Catalunya, 3,6% foreigners)*<br>*1,671,449 health cards*<br>*Average life expectancy at birth: 83,0 years* |
| *Offices* | |
| *Commerce* | *In Barcelona there is a wide and well-stablished network of proximity commerce, but also shopping centers.* |
| *Hotels, bars and restaurants* | *537 hotels with 34,269 rooms*<br>*2.283 congresses and conventions, with 647.693 delegates* |
| *Other (arts, sports,...)* | *Arts and entertainment:*<br>*37 libraries with 6,178,297 visits and 4,467,274 borrowed documents, 8 archives.*<br>*34 museums, 7 exhibition centers, 7 places of architectonic interest.*<br>*203 cinemas with 7,125,274 visitors, 57 theaters with 2,816,283 spectators, 16 live music rooms.*<br>*Sports:*<br>*1,776 public sports facilities* |

### 4.3.4 Manufacturing and construction

The same analysis can be carried out including also variables relevant for socio-economic analysis. There was not available disaggregated information on Useful Surface (US) or energy carriers for categories in Manufacturing and Construction, or even economic reports on the sub-sectors taking part in industrial activity in Barcelona. However, we can discuss partial results to explore possible further research. An example of comparison over sub-compartments of Manufacturing and Construction based on variables relevant for socio-economic analysis (Human Activity and Value Added) is given in Fig. 5.6.

Construction has a large share of HA and the largest share of VA (almost 50%), even being 2012 a year with less activity of construction of new buildings in relation to pre-2008 years before the real-estate bubble burst.

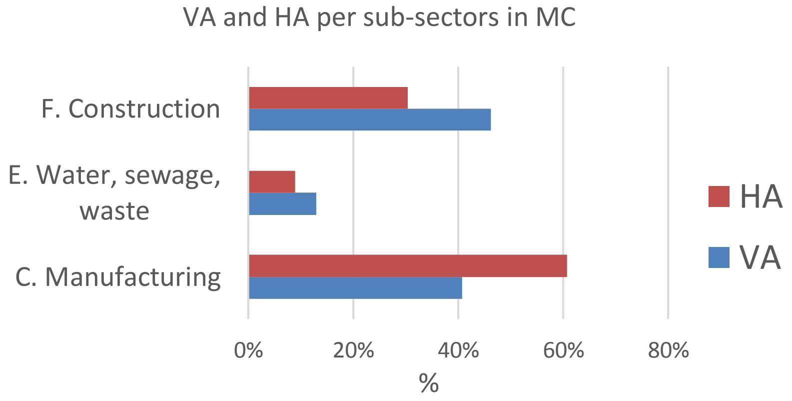


*Figure 4-16 Comparison of the level of employment (HA in Paid Work) and the contribution to the Gross Value Added (VA) over the three sub-sectors of Manufacturing and Construction*

### 4.3.5 Mobility – analyzing the user side

There is another interesting feature of this approach that makes it possible to re-arrange à la carte the definition of categories to be included in the end-use matrix.

If we want to study possible changes to the current situation, we have to study how the generic function changes as the arrangement of the lower level elements change. For example, when dealing with mobility we have two different categories that are in different boxes in the dendrogram: Private Mobility and Public Transport. The implementation of a policy aiming the reduction of private mobility and boosting public mobility must be analyzed by the changes that will make on the generic function: Mobility. To do so, we should change the definition of categories and design a different end-use matrix with private and public mobility using HA of the user instead of the worker, as it is shown in Table 4-14. Besides being an interesting example to see the user side of human activity, it also gets to the structural element level.

Due to the fact that previous MuSIASEM analysis focused on primary and secondary sectors, the only Human Activity was the one of the workers. The metabolic characterization of these sectors explains their capitalization in the Paid Work sector, i.e. the power capacity and the energy carriers required. In the case of the Residential category, it shows the material standard of living. Nevertheless, when analyzing the service sector, users play a relevant role and must be included in the accounting. For example, as the bus driver earns a salary to drive the bus, there are passengers that make use of the service. Then, we are not only accounting the HA of paid work in relation to the energy metabolized, but also the HA of users. This new accounting allows us to evaluate the services in relation to the quality of the service relating the time of worker vs the time of user, the time that the user spends to get services, the Useful Surface available per Human Activity of user and worker, or the energy requirements that the service demands.

*Table 4-14 Special End-use Matrix describing the metabolic pattern associated with the final cause "Mobility" using categories of human activity defined in Outside Paid Work*

| | HA *(user)* | EMR *(user)* | | | ET | | | Distance |
|---|---|---|---|---|---|---|---|---|
| | | Elect. | Heat | Fuels | Elect. | Heat | Fuels | |
| | Mh | kWh/h | MJ/h | MJ/h | GWh | TJ | TJ | Gm |
| **MOBILITY** | **593** | **0.5** | **0.7** | **17** | **303** | **419** | **9,434** | **8,990** |
| PRIVATE MOBILITY | 401 | 0.1 | 0 | 17 | 46 | 0 | 6,620 | 4,884 |
| Active | 289 | 0.1 | 0 | 0 | 15 | 0 | 0 | 1,588 |
| Private motorized | 112 | 0.3 | 0 | 59 | 31 | 0 | 6,620 | 3,296 |
| PUB. TRANSPORT | 192 | 1.3 | 2.2 | 17 | 257 | 419 | 2,814 | 4,105 |
| Collective pub. transp. | 180 | 1.6 | 2.3 | 10 | 291 | 419 | 1,293 | 3,598 |
| Taxis | 12.2 | 0.4 | 0 | 125 | 5 | 0 | 1,521 | 507 |

An assessment of distance is also shown, which is another interesting variable to analyze when discussing mobility. Distance might be a better indicator than HA to analyze performance in this case. Moreover, many users would consider the speed and flexibility of Private motorized as an asset to its use. In this example, active modes of transport are those where most time is spent, but where less kilometers are made after Taxis.

### 4.3.6 Residential sector – spatial analysis

In relation to the residential sector, we had a significant amount of data which made possible an analysis by *barrios. Barrios* are administrative sectors of the city. Each barrio is fairly homogeneous in socio-economic and built environment terms. Therefore, its average characteristics enable an identification of factors affecting energy consumption. This means that we can get an end-use matrix characterizing the residential sector per barrio. To visualize appropriately all this information and ease the analysis of the results, we use graphs, but other visualizations could be useful, such as maps. We make a preliminary analysis of the possibilities of the tool looking for correlations of EMR and EMD with diverse variables that characterize the *barrios.*

It should be noted that assessments of energy end use are in this case calculated in an overall amount of Gross Energy Requirement in thermal equivalent, using the partial substitution method. This is a reasonable assumption since the shares of heat and electricity are almost exactly same in all the barrios, the shape of the graphs would not change when changing the ratios to those only for electricity or heat. The issue of how to handle the aggregation of quantities of energy referring to carriers of different qualities has been discussed in Section 3.2.2.

As it has been said, ET data was provided by the Agència de l'Energia, so we did not build the data top-down in function of structural elements. However, as it was communicated to us, this data was generated by a classification of buildings by age and was characterized by the typical constructions and technologies of that period and other features of each specific building (height, orientation, age, etc.). A more complete construction would include other factors:

(i) the demographic profile of the households, considering the size and composition in terms of age, gender, number of children, etc.
(ii) the effect of economic variables, considering income, unemployment rate, etc.

We consider EMRs in the residential sector as a proxy of the material standard of living: the number and energy-intensity of appliances metabolizing energy inside the houses. On the other hand, Exosomatic Metabolic Density (EMD) is a variable already in use in technical assessments of energy efficiency in buildings, energy carrier consumption per m$^2$ of the dwelling. Looking at the graphs in Figure 4-17 Exploring the effect of average Building Use per inhabitant on EMR and EMD of the residential sector at level n-5 (73 barrios)Figure 4-17 and Figure 4-18 we can see that EMR is correlated with the amount of Building Use per inhabitant and with familiar income. The shapes of the two graphs are very similar since this two variables are correlated as well. This is, rich people enjoy more space in their homes.

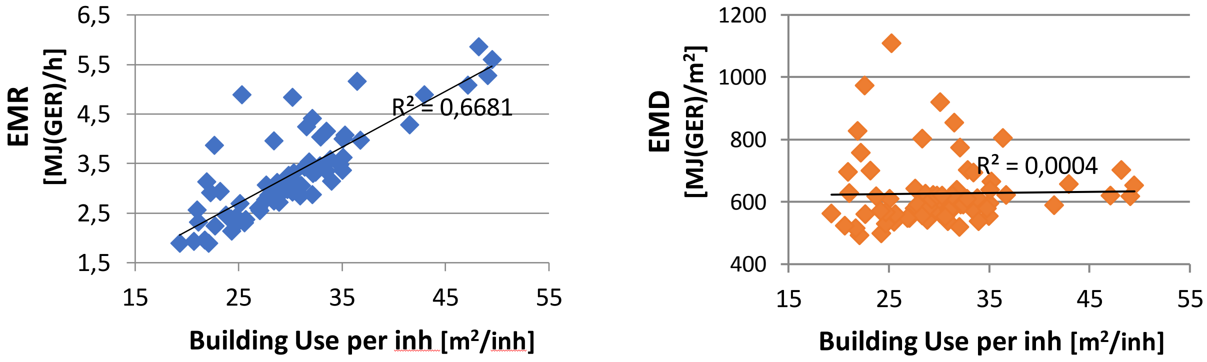


*Figure 4-17 Exploring the effect of average Building Use per inhabitant on EMR and EMD of the residential sector at level n-5 (73 barrios)*

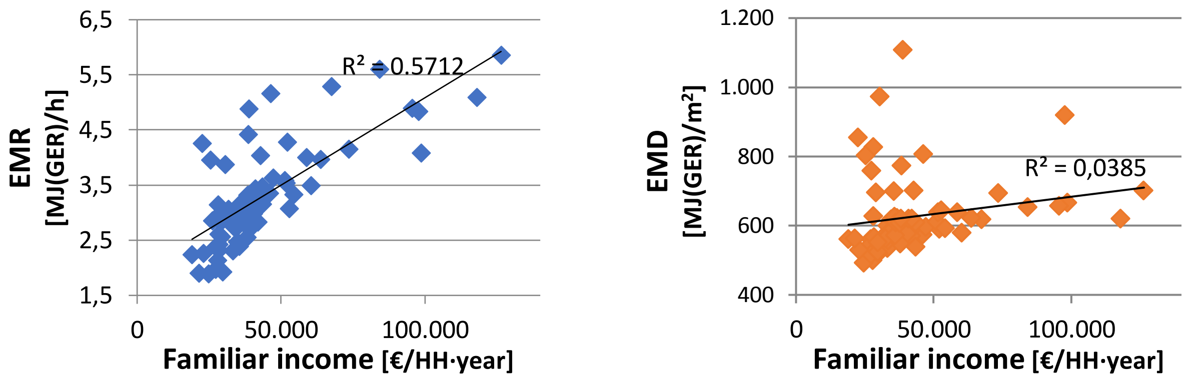


*Figure 4-18 Exploring the effect of average familiar income on EMR and EMD of the residential sector at level n-5 (73 barrios)*

When looking at more technical variables like year of construction of the buildings (Figure 4-20), an inconclusive analysis is found. We consider the Multi-storey index of residential buildings (MSI) as the number of floors that buildings that include dwellings have. This shows no correlation with EMR, as shown in Figure 4-19. However, EMD has a shape similar to that of Building use per inhabitant and Familiar income. We can say that a large amount of barrios show a shared trend in those 3 variables. There are outliers having high EMD at low Building use per inhabitant, low familiar income and low MSI. These outliers represent a low amount of citizens due to the low density of buildings. It is said that taller constructions improve efficiency in relation to heating (IDAE, 2011). However, it must be taken into account that heating does not represent a large share of the residential consumption since Barcelona has a Mediterranean climate, with mild winters. In our case, MSI not necessarily represents the explanation for differences in the value of EMD. It is true that at lower MSI there are the higher values of EMD, but there are also have the lowest EMD of the 73 *barrios*.

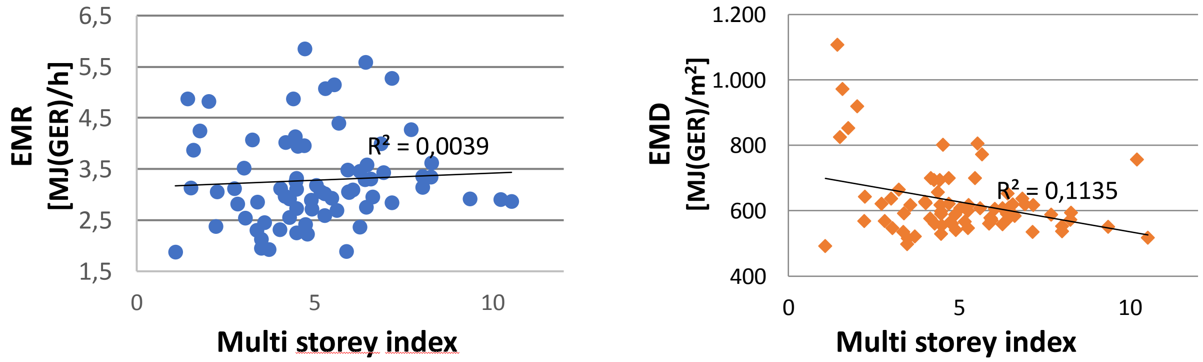


*Figure 4-19 Exploring the effect of average multi storey index on EMR and EMD of the residential sector at level n-5 (73 barrios)*

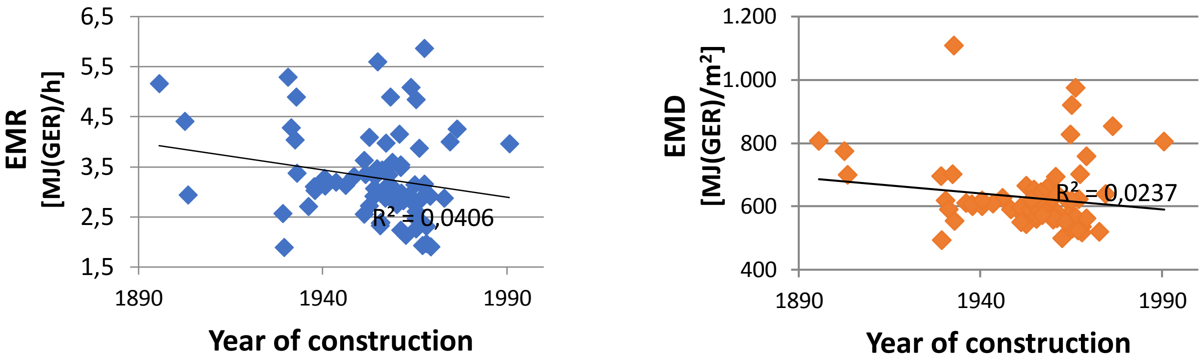


*Figure 4-20 Exploring the effect of average year of construction of buildings on EMR and EMD of the residential sector at level n-5 (73 barrios )*

In conclusion, many factors have to be considered to be able to explain the values of $EMR_i$ and $EMD_i$. Taking any conclusions would require a deeper analysis of the relation of the variables, and the inclusion of other variables that could affect the relations: efficiency and quantity of devices, energy poverty, accuracy of the hours spent inside homes, care paid work, unemployment, quality of insulation of buildings, etc. In general, we can see that richer people have larger homes, with higher energy consumption and EMR possibly due to the larger use of more appliances, even if they could be newer and more efficient. The effect on EMD does not seem as strong, since they have a larger area. At lower incomes there is a large diversity and no clear trend can be determined for EMD, but the outsiders presenting high EMD and low familiar income could be related to high density of devices and/or less efficient devices or buildings.

In this brief discussion on the residential sector, we can see how relevant is the combination of spatial analysis within the holistic view of the different functional compartments defined in the multi-level End-Use Matrix. This implies that the proposed approach makes it possible to take full advantage of the power of Geographic Information Systems, a key tool in urban planning and environmental assessment.

# 5 The findings of this exploratory application

(Lead author Mario Giampietro)

## 5.1 The innovative aspects of the methodology proposed in this deliverable

In this deliverable we have started discussing current policies and frameworks for cities trying to fix different environmental problems related to energy. The Covenant of Mayors represents the main reference of European policy in this topic. PECQ is the current policy framework for Barcelona inside that framework. As we have discussed in Section 1 and 2 both programs use generic targets and propose ambiguous methods for monitoring them, which could generate different problems. Trying to solve these problems, we have developed and proposed here an alternative method for the analysis of the urban metabolism (Section 3), illustrating it with the case of Barcelona (Section 4). The quantitative results discussed in section 4 are just exploratory and their value will increase through the power of comparison when similar analysis of other cities are available. Therefore, the main results of this analysis are not quantitative, but epistemological and could be summarized in two aspects: (i) move away from the concept of energy efficiency of a city and; (ii) move away from providing predicative representations chosen by the analysts. For solving the first issue, we propose to use the concept of energy performance of a city, which moves away from a mono-scale and mono-dimensional quantitative analysis toward a multi-scale multidimensional quantitative analysis. In the case of the second issue, we propose to move away from predicative representations chosen by the analysts (deterministic results based on uncontested definitions and assumptions) toward impredicative representations chosen by the users of the analysis, contingent results reflecting the unavoidable existence of contested definitions and assumptions. A summary of these aspects is presented below through five bullet points.

1. ***Move away from the concept of energy efficiency of a city, toward the concept of energy performance of a city***

   In this deliverable we have presented an innovative approach that can be used to both identify the relevant factors determining the energetic performance of cities and characterize their metabolic characteristics. As explained in the introductory sections of this document and in a previous deliverable of EUFORIE (Giampietro, Velasco-Fernández and Ripa, 2017), the concept of efficiency is simplistic and it can not provide a useful analysis of the behavior of complex adaptive reflexive, self-maintaining and self-reproducing systems. Therefore, the individual outputs of the actual models, indicators and targets when used one at the time to guide energy policy generate hypocognition in relation to other relevant dimensions and levels of analysis as discussed in section 1 and 2. For this reason, when analyzing the complex set of energy conversions taking place in a city it is not advisable to use the concept of efficiency: an indicator based on the ratio of just two numbers. The integrated set of metabolic characteristics described using the approach proposed here makes it possible to move to the concept of performance described by an integrated set of indicators, whose values are affecting each other across levels and dimensions of analysis. For example, relating global environmental problems as climate change with local ones, the performance and the option space of a city.

## 2. *Moving away from a mono-scale mono-dimensional quantitative analysis of efficiency toward a multi-scale multidimensional quantitative analysis of performance*

Studying the energetic performance of a city requires identifying different sets of relevant factors that can only be observed when perceiving and representing the performance of a city at different levels of analysis: (i) the whole city; (ii) the constituent components of the city; (iii) the functional elements, which in turn can be described as specific operational couplings of functional and structural elements – i.e. holons. Therefore, these factors are both material, i.e. structural elements described in physical terms, and immaterial, i.e. functional elements described in notional terms.

In addition to the need of organizing at different levels, we have also to integrate different dimensions. In particular:

- *the socio-economic and the demographic dimension* can be considered by the metabolic rates, which map energy and monetary flows against the hours of human activity of the constituent components. These constituent components are categories of human agents (identities) having decision powers (agencies) and expressing different final causes (teleologies). Then, when describing the patterns of energy conversions in terms of flows of energy carriers per hour of human activity, we generate benchmarks that can be associated with the technical characteristics of technologies used in functional elements, and/or with sociodemographic characteristics of the population: age, gender, education, migration background and ethnicity, religious affiliation, social class, family type, employment, income, barrio, etc.
- *the biophysical and ecological dimension* can be considered by metabolic densities, which map the energy and monetary flows against areas of land uses of the constituent components, for example, administrative units. Then, when describing the patterns of energy conversions in terms of flows of energy carriers per categories of hectares of land uses, we generate benchmarks that can be associated with the characteristics of the processes taking place within functional elements. For example, kWh of electricity consumed per m$^2$ of apartment in the

residential function. The family of indicators of performance based on metabolic densities can be used to describe the performance of the city in relation to (i) the impact on the environment and ecological constraints, including the ecological processes embedding the city; (ii) internal attributes of the barrios or households that determine planning requirement (e.g. type and number of equipment, transport mode) or household characteristics (e.g. apartments, terraced houses, isolated house).

### 3. *Moving away from predicative representations (deterministic results based on uncontested definitions and assumptions) toward impredicative representations (contingent results reflecting the unavoidable existence of contested definitions and assumptions)*

The information space generated by the end use matrix is a set of relations over relevant attributes of a city represented across levels, scales and dimensions of analysis. This system of accounting does not establish a clear direction of causality over the values shown in the cells of the end-use matrix. The value written in a cell can be determined by information coming top-down, available statistics defining functional elements at a large scale, or bottom-up, with technical coefficients of structural elements measured at the local scale. That is, the nature of this information space makes it possible a many-to-one mapping of potential external referents, i.e. different sources of the data. For this reason, we can face situations in which we find contrasting values for the same cell depending on the chosen source. We claim that this redundancy should not be considered as a problem but rather a major value of the approach, since is allows:

(i) to calculate in two non-equivalent ways the same value and so to check the robustness of the data by looking for incongruent results when estimating the data going into a given cell;

(ii) to generate in non-equivalent ways the representation of specific elements indicates the epistemological difference of the proposed approach from the conventional strategy of quantitative analysis. The proposed approach can be used in two different modes:

  - *for diagnostic purposes* – describing the system in the best way possible by estimating the values in the end use matrix with diverse data sources;
  - *for anticipatory purposes* – exploring the option space of new combinations of values within the given set of relations.

This difference is extremely important in relation to the quality of the quantitative output generated. An approach based on relational analysis generates quantitative analysis providing contingent anticipation – “what if” representations to explore different options and solutions of political relevance. Moreover, this approach is transparent in relation to the political implication of the pre-analytical choices and allows the co-production of knowledge in participatory processes for improving the quality of the quantitative representation for supporting decisions (Benessia *et al.*, 2016). This represents a change on the relation between policy and science. Policy makers must move away from looking for scientific reports validating their decisions, and start looking for information relating the dimensions relevant for the different actors, in a way that the tradeoffs among these dimensions are carefully evaluated in order to take informed decisions.

### *4. Moving away from models providing representations chosen by the analysts, toward an approach generating representations chosen by the users of the analysis*

Total transparency in the framing and the consequent construction of the relations over chosen categories of accounting implies that the users of the results can choose à la carte: indicators, representations, assumptions, sources of data. The proposed set of relations to be used for the analysis can be explained and made available online to facilitate the quality check from an extended peer community.

Put in another way, the proposed approach is totally compatible with the philosophy of Post-Normal Science (Funtowicz and Ravetz, 1993). However, especially when dealing with the study of cities the availability of data can represent an important constraint to the definition of indicators, it is in continuous evolution and has a lot of grey areas of human activity. Yet the redundancy and flexibility of accounting given by the end-use matrix helps in dealing with this predicament better than when using more conventional approaches. For example, conventional optimization models that make difficult to track the different implicit hypothesis and pre-analytical choices, e.g. the HISPALINK predictions used in PECQ (Ajuntament de Barcelona, 2011).

### *5. Moving away from "dead quantitative assessments done once and for all", toward "living and flexible information spaces used for co-production of knowledge"*

As stated earlier, the examples presented in Section 4 rather than an illustration of results should be considered as an illustration of an epistemic tool that can be used by a community of people interested in studying the performance of city to better interact when learning together how to improve their understanding of the issue. In fact, the relational analysis presented here can be used to:

(i) discuss the basic ontological assumptions of the accounting: what is Barcelona? what are the constituent components conforming its identity?
(ii) identify relevant factors missed in the existing framing and analysis;
(iii) learn which factors should be considered in relation to which relevant issues to generate a better integrated set of indicators;

(iv) check the robustness of proposed analysis and data, identifying knowledge and data gaps;

(v) verify the usefulness of approach when used to compare cities having different characteristics and operating in different contexts. How should we use this approach in order to compare "apples with apples and oranges with oranges" when looking for best practices in relation to specific functional elements operating in similar or different contexts – e.g. when comparing the performance of Helsinki with the performance of La Havana?

## 5.2 Cities as open systems: how to calculate emissions?

Cities are open dissipative systems and therefore their survival depends on the maintenance of favorable boundary conditions that in turn require processes taking place outside their border. Two simultaneous conditions must be fulfilled:

(i) internal viability – the system is able to express a set of transformations reproducing its own structural and functional elements.

(ii) external feasibility – the process of self-organization takes place in an admissible environment of favorable boundary conditions: inputs are available and wastes can be dumped.

Activities carried out inside the city – what is included in the end-use matrix – cover only a small fraction of the resources required by the city to stabilize its metabolism: the resources needed for food products, water inputs, energy carriers, material products. At times even services provided in the city are externalized, e.g. call centers, online shopping. Therefore, any approach aimed to frame environmental issues in an urban system should consider the possibilities of cost-shifting strategies when optimizing local processes. So, in order to proper frame the analysis of the metabolism of a city it is important to have a clear idea of: (i) internal consumption of energy carriers; (ii) consumption of primary energy sources to produce the carriers; (iii) level of externalization of production factors – by checking the fraction of the internal inputs consumed in the end-use matrix and produced inside the city versus the fraction imported from the outside.

In this deliverable we have not calculated the GHG emissions of Barcelona. However, considering that cities are open systems we have discussed the importance of the pre-analytical choices when doing that. In this sense, a proper characterization of the emissions generated by an urban system have to take into account:

*1. direct (or local) emissions* - The emissions taking place inside the borders of the city determined by energy and non-energy activities: emissions coming from direct combustion by activities happening in the city: cars, combined cycle plant in power, fugitive emissions or other emissions (land use change, etc.).

2. *indirect emissions* – The emissions derived of the energy sector allocated out of the borders of the city but related to the energy carriers and primary energy sources used for end-uses taking place inside the borders of the city: electricity production, mining of coal, gas transport, oil refineries.

3. *embodied emissions* – The emissions referring to processes of production of non-energy imported inputs that are consumed by the end-uses taking place inside the borders of the city. This family of emissions tends to be neglected in the standard protocols such as the Covenant of Mayors. However, they become very important when considering: (i) the consumption of energy inputs and other resources such as water required to produce in rural areas the food and mining of raw materials consumed by a city; (ii) the production and transportation of the durable and non-durable goods; (iii) the alteration of environmental processes due to the dumping of the wastes generated by the city; and (iv) the residential and services required to reproduce part of the working force represented by commuters. Large cities use to present a positive balance with their peripheries, attracting workers and shifting the cost of their reproduction.

On the other hand, not only products are manufactured and transported from out of the system, but also people come in and out continuously of the system. Residents are not the only relevant actors in the metabolism of the city, there are also the commuters living in cities nearby and tourists. This fact makes that indicators per capita that only take into account residents do no capture the whole reality. Alternatively, we have purposed in this deliverable a method of accounting that distinguishes between different constituent components: residents, commuters and tourists, which have been characterized using hours of Human Activity [h/year]. Moreover, we have related them with the different activities performed in the city.

## 5.3 Problems and limitations

As have been already mentioned many times during this report, this study just validates the usefulness of the results in theoretical terms, a complete validation requires an actual participatory process with the social actors and the administrators of the city of Barcelona. This is an important pending step that has to be done before being able to give a complete and final assessment of the usefulness of the proposed method.

Additionally, we can mention other problems and limitations in relation to the methods presented here. While we discovered that the end-use matrix has great potentialities we also learned about its problems and limitations. These limitations could be summarized in three bullet points:

1. ***it requires of a lot of heterogeneous data coming from different sources.*** At times the required data are not available, inconsistent or of dubious quality, especially in

relation to the statistics of human activity and the activities in the shadow economy. It should be noted that this predicament is unavoidable for this type of studies. On the positive side, the Sudoku effect generated by the end-use matrix makes it easier to identify missing data, inconsistencies and to generate estimates in the case of missing data by crossing data from different sources.

2. ***it requires the collaboration of the various offices collecting the data and generating the statistics.*** In fact, the taxonomy of data to be used in the end-use matrix can be different from the one used by the statistical offices. This would require the collaboration with those collecting and elaborating primary data. Many statistical offices collaborate and make their outcomes more useful to the users. However, they also present resistance to generate changes over the existing protocols. These changes could generate discontinuities over historical records or would require extra loads of work that are not easy to assume with the resources they have.
3. **it requires the involvement of the users of the study in the definition of the protocol of accounting.** The system of relations over the data across levels and categories implies that the quantitative analysis is impredicative, the results are contingent on the choice of assumptions and definitions. It should be noted that rather than a problem this should be considered as a virtue because this implies that this method can only operate in co-production.

## 5.4 Possible applications of this approach

As discussed in Section 1 and Section 3 both for practical and in theoretical reasons it is not possible to define in an uncontested way and use in a satisfactory way a single protocol to assess emissions or embodied quantities or to define ultimate targets for the sustainability of cities in general terms. The analysis of the sustainability of cities requires always to be contextualized in relation to specific geographic and historical contexts and specific temporal situations. Moreover, the complexity of the concept of performance requires that the quantitative analysis generated to support decision has to be coproduced in participatory processes dealing with specific problems. This implies that an assessment of the energetic performance of a city cannot be done in general. This is why we call the exercise carried out in this deliverable an exploration of the potentiality and applicability of the method rather than a study of the performance of the metabolism of Barcelona.

Therefore, as already mentioned in section 5.1, this approach should be used to develop a living information space that can be used for a co-production of knowledge by epistemic communities interested in the metabolic pattern of cities. This living information space should be tailored, depending on the circumstances, to specific issues. We can imagine the development of a software organizing available data that can be available through an interactive website. Similar as it has already been done for the Covenant of Mayors with conventional accountings, authorities could check the end use matrix of other cities. At that point, one could compare cities by sectors and subsectors in similar contexts and not by general benchmarks without contextualization. This living dataset can be used to:

1. sustain a permanent process of quality control of the information, using the same idea of Wikipedia, by cities' administrations, experts, and journalists and citizens to monitor and oversee political decisions;
2. inform a participatory process of deliberation on the policies aimed at improving the sustainability of cities;
3. learn how to standardize a quantitative characterization of the metabolic pattern of cities to prime a process of mutual learning among cities. After reaching a certain level of reliability and confidence, this tool-kit could be used by different cities of the world to share their experiences about: (i) analytical tools - how to analyze and how to improve their energetic performance; (ii) best practices - how to solve practical problems by studying the efficacy of specific functions in relation to final cause (contextualized problems) and of specific structural elements in relation to specific functions (technical problems); (iii) effectiveness of policies – by comparing within a standardized framework the results.
4. negotiate environmental agreements between cities in a transparent way. Thanks to the transparent way of characterizing the urban metabolism, cities can monitor and quantify the socio-economic aspects that they are sacrificing in favor of the environment. This is a crucial issue when building trust between different actors when developing a common agreement. Without a transparent and quantitative way of monitoring the agreements, they become superficial or just empty rhetoric, with the risk that they will bring in their hidden agendas as greenwashing or creative destruction that would be contrary to what is declared as it is explained in section 1. Moreover, this monitoring would be useful for detecting breaches and amendments of the covenants, which is necessary to develop penalties when the agreement is broken or to evaluate the grade of achievement.

Additionally, the end use matrix could be expanded to integrate other relevant issues as food, water, waste, use of time and space, demographics, material standard of living, level of services, inequities, etc. Some of this nexus analysis can be found in previous (Giampietro *et al.*, 2014; Velasco-Fernández, Ramos-Martín and Giampietro, 2015; Chifari *et al.*, 2017; Kovacic and Giampietro, 2017) and current works (*magic-nexus.eu)*.

# A APPENDIX 1. Detailed explanation of data processing

(Lead author Laura Pérez-Sánchez)

## A.1 Introduction

In this appendix we illustrate in detail the processes adopted to integrate non-equivalent data sources to generate the end-use matrix of Barcelona, specifying the assumptions used. As almost all data has been collected with a different purpose that the purpose of our study, it doesn't shape perfectly in many of the categories of our accounting. To illustrate the process we will make reference to the scheme presented Table A-1. Red capital letters relate to the calculations that are explained exhaustively in the subsequent text following the alphabetical order of the references. Different functional elements in the organization might have the same reference. For example, private motorized and taxi share the same reference B.

*Table A-1 Scheme of references to the calculation strategies of the end-use matrix*

| | | | HA | US | ET | VA |
|---|---|---|---|---|---|---|
| | | | h | $m^2$ | GJ or kWh | € |
| OUTSIDE PAID WORK | **RESIDENTIAL** | | | | | |
| | | 73 barrios | A | K | P | - |
| | **MOBILITY** | | | | | |
| | | Private motorized | B | L | Q | - |
| | | Active | C | | | |
| | | Taxi | B | - | | |
| | | Collective public transp. | D | | | |
| | **USE OF SG** | | | | | |
| | | Education | E | - | - | - |
| | | Healthcare | F | | | |
| | | Offices | | | | |
| | | Commerce | | | | |
| | | Hotels | | | | |
| | | Bars and restaurants | | | | |
| | | Other | | | | |
| | **OTHER OUTDOOR ACTIVITIES** | | G | L | - | - |
| | | | | | | |
| PAID WORK | **SERVICES & GOVERNMENT** | | | | | |
| | | Education | H | M | R | V |
| | | Healthcare | | | | |
| | | Offices | | | | |
| | | Commerce | | | | |
| | | Hotels, bars and restaurants | | | | |
| | | Other | | | | |
| | | Taxi | B | n.a. | Q | n.a. |
| | | Collective public transp. | I | | | |
| | | Transport of goods | B | K | | |
| | **PORT** | | J | N | S | W |
| | **MANUFACT. & CONSTRUCT.** | | H | M | T | V |
| | **ENERGY SECTOR** | | | O | U | |

## A.2 Broad explanation of the organization

First of all, a small introduction to the functional elements and the interaction of their variables will be made, since we are ordering the explanation by variables.

### A.2.1 Residential

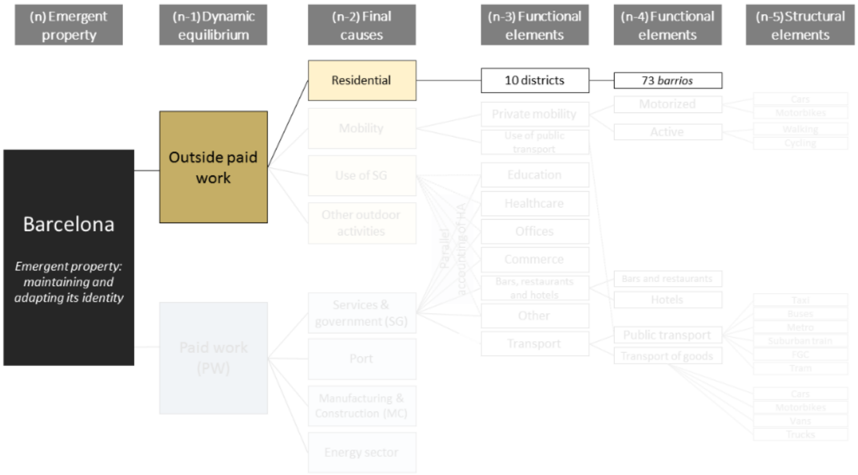


*Figure A-1 Situation of Residential in the general organization dendrogram of the system*

The residential sub-sector includes all activities happening inside the physical boundaries of households and they are not associated with the generation of value added. Among these there are parts of: physiological overhead (sleeping, eating, etc.), unpaid work (cooking, washing clothes, dishes, etc.) and culture and leisure (playing, reading, watching TV, etc.).

The built environment consists mainly of apartment buildings, but with great variety of ages, sizes and qualities, and still also a part of detached houses. In further analysis the effect of these different structural elements can be made. However, in this first assessment the distinction was made in base to constituent components, the 73 *barrios*.

## A.2.2 Mobility/transport

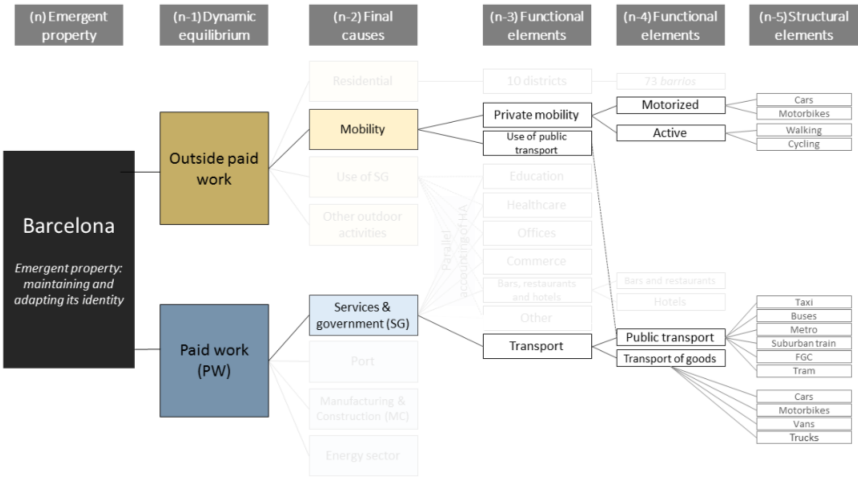


*Figure A-2 Situation of mobility/transport in the general organization dendrogram of the system*

Mobility and transport are those activities related to the movement of people and goods inside the city, independently of the origin or final destination or the place of residence or work of the driver and occupants. Thus, in the end-use matrix the part of the trip included is that happening strictly inside the boundaries of the city. The activities in this group are divided in three, and have structural elements at level n-5:

- private mobility, which is only included in Outside Paid Work:
    - active: walking and cycling.
    - motorized: cars, motorbikes and vans.
- public transport, which has two sides: that of the worker (whose HA is included in PW and to which US and ET are allocated) and that of the users (HA only variable included in OPW)
    - individual: taxi
    - collective: metro, bus, tram, FGC, *suburban train*.
- transport of goods and services, included only in PW:
    - different types of vehicles: cars, vans, trucks and motorbikes.

These elements are included in different functional elements in our dendrogram, but the data usually comes from the same sources, and so the calculations are tightly related. The calculations will be made at the level of the structural elements, this is, with technical coefficients mainly: traffic data, occupation of vehicles, number of trips in public transport, energy consumption per km, etc. The assessment of its US is complicated since different categories share the same area and so an allocation strategy is required. E.g. Motorized Private Mobility, a part of public mobility, transport of goods and even cycling (in Active) is carried out in roads. In general, streets are public spaces where a great variety of activities are held: going for a walk, terraces of bars, cycling for leisure or mobility, waste management and police transport, etc. This opens a new debate and the strategy used is only a first approach.

Also, the workers and companies included in the category Transport of goods and services might or might not be registered in the same city, and even if they are registered in the city, they might have another principal activity other than transport (police, waste management, construction, repair, medical assistance, etc.). This fact makes it difficult to allocate flows of VA and HA to this category and implies the risk of potential double counting.

### A.2.3 Services and Government not related to transport (Education, Healthcare, Offices, Commerce, Hotels, Bars and Restaurants, Other):

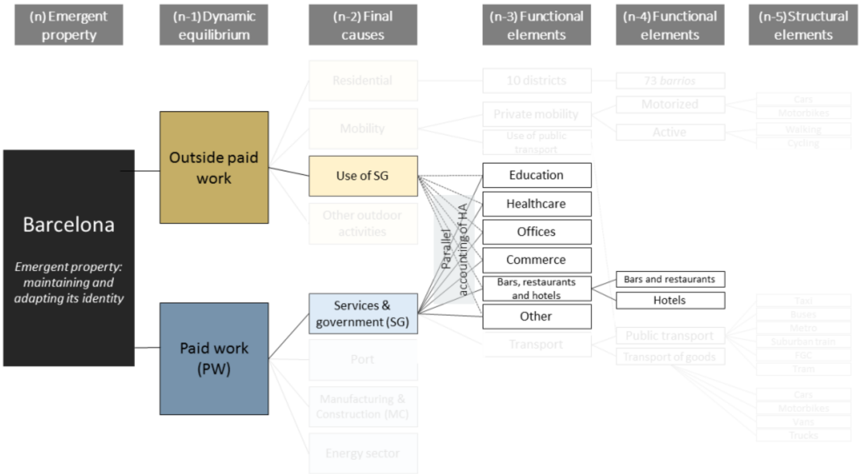


*Figure A-3 Situation of Services and Government not related to transport in the general organization dendrogram of the system*

The activities inside Services and Government sector different than transport are mainly carried out inside buildings. Categories were defined referring to general functions, in this preliminary analysis structural elements were not assigned to the different functions. There is a huge variety of activities carried out at different scales (e.g. shops vs supermarket in commerce) and within different administrative regimes (e.g. offices in the private and public services). The analysis of the service sector of the city requires a collaborative effort joining the inputs of different types of expert.

There is a parallel accounting of HA, with the HA of the users, which is allocated in Outside Paid Work and for which the effect of commuters and tourists has to be taken into account, which required assumptions. The introduction of this parallel accounting allows to relate the overall analysis of the metabolic pattern of the city with the quality of their services, which could be evaluated as the numbers of users by service provider, for example, students per teacher, doctors per capita, etc. The other variables in the files of users in the end-use matrix do not have VA, ET or US, and so, none of the ratios. This is done in order to avoid double counting, but an analysis of the metabolic patterns from the consumption side could be made taking the variables in the PW element. In Table A-2, the correspondence of the MuSIASEM elements with the categories of the Gross Value Added, Human Activity (PW) and Built Environment datasets is shown.

*Table A-2 Correspondence of the categories of the datasets for GVA, HA and US for the elements of Services and Government at the n-3 level*

| MuSIASEM category | **(V)**-Gross Value Added (classif. CCAE) | | **(H)**-Human Activity (PW) (classif. CCAE-2009) | | **M** - US |
|---|---|---|---|---|---|
| | Economic activity | Allocation | Economic activity | Allocation | |
| Commerce | 45. Venda i reparació vehicles de motor i motocicletes | Commerce | G. Comerç i reparacions | Commerce | Commerce |
| | 46. Comerç engròs i intermediaris, exc. vehicles motor | Commerce | | | |
| | 47. Comerç detall, exc. vehicles motor i motocicletes | Commerce | | | |
| Hotels, bars and rest. | 55-56. Serveis d'allotjament, menjar i begudes | Hotels, bars and rest. | I. Hostaleria | Hotels, bars and rest. | Hotels, bars and rest. |
| Offices | 58-60. Edició i serveis audiovisuals | Offices | | | |
| | 61-63. Telecomunicacions; serveis informàtics i serveis informació | Offices | J. Informació i comunicacions | Offices | Offices |
| | 64-66. Activitats financeres i assegurances | Offices | K. Activitats financeres i d'assegurances | Offices | |
| | 68. Activitats immobiliàries | Offices | L. Activitats immobiliàries | Offices | |
| | 69-71. Activitats jurídiques i comptables, de consultoria i serveis tècnics | Offices | M. Activitats professionals, tècniques | Offices | |
| | 72- Recerca i desenvolupament | Offices | N. Act. administratives i serveis auxiliars | Offices | |
| | 73-75. Publicitat; altres activ. professionals i tècniques; activ. veterinàries | Offices | O. Administració pública | Offices | |
| | 77-82. Activitats administratives i serveis auxiliars | Offices | U. Organismes extraterritorials | Offices | |
| | 84. Administració pública, Defensa i SS obligatòria | Offices | S. Altres serveis | Offices and other | |
| | 87-88. Activitats serveis socials | Offices | | | |
| Education | 85. Educació | Education | P. Educació | Education | Education |
| Healthcare | 86. Activitats sanitàries | Healthcare | Q. Act. sanitàries i serv. auxiliars | Healthcare | Healthcare |
| Other | 90-93. Act. artístiques, recreatives i d'entreteniment | Other | R. Activitats artístiques, recreatives | Other | Other |
| | 94-98. Altres serveis i activitats llars | Other | T. Llars que ocupen personal domèstic | Other | Sports |
| | 52-53. Emmagatzematge i activitats afins al transport; activitats postals | Transport and Other* | S. Altres serveis | Offices and other | Spectacles |

*The inclusion of the category of GVA related to transport and port activities in the category Other is explained in the correspondent sub-section

### A.2.4 Other outdoor activities

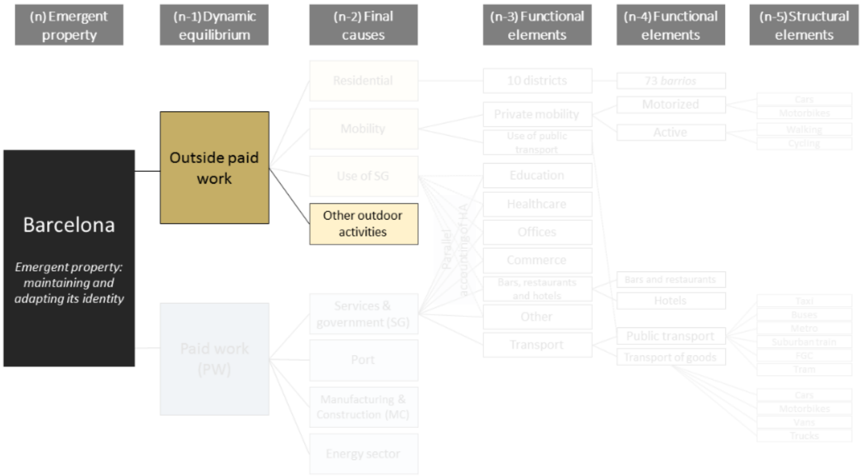


*Figure A-4 Situation of Other outdoor activities in the general organization dendrogram of the system*

Other outdoor activities refers to the activities held in public space that don't belong to Paid Work or Mobility: going for a walk, going to the beach, playground, etc. These are a significant share of the time spent in the city, essential for the closure of the human activity, and the three constituent components take part (residents, commuters and tourists). In this case, since space of roads and sidewalks is already accounted in transport/mobility elements, the US will be that of parks and other natural areas in the city, in order to get closure of the US of the city. Also, they don't have ET or VA in the end-use matrix, the possible ET happening in public space, like public lighting, are allocated to other elements.

### A.2.5 Port

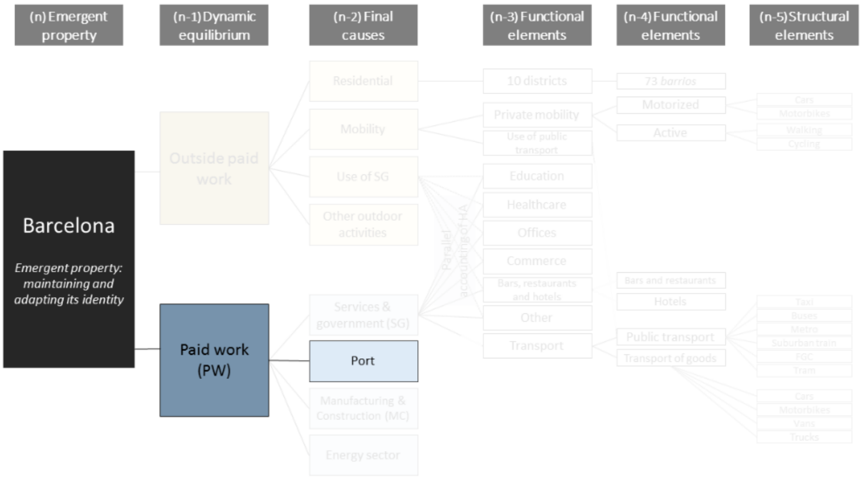


*Figure A-5 Situation of Port in the general organization dendrogram of the system*

The activity of the port is a sub-category of PW. It is a large infrastructure which contains diverse activities: fishery, marina, logistics, cruise ships, administrative offices, and a whole system of internal transport, with trains, cranes, trucks, and road vehicles. This element had to be inserted in the system considering that it has activities from all sectors of economy, and so a careful re-calculation of the elements had to be made. Moreover, the port is located in between the *barrio* “Marina del Prat Vermell” and in the municipality of Prat de Llobregat.

*Figure A-6 An overview of the port of Barcelona*

## A.2.6 Manufacturing and Construction

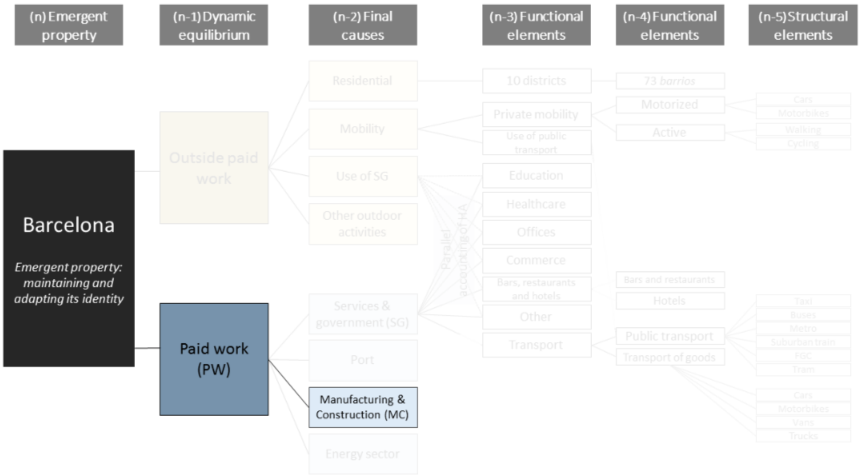


*Figure A-7 Situation of Manufacturing and Construction in the general organization dendrogram of the system*

Manufacturing is a sector losing weight in the economy of the city and the datasets that could be found didn’t disaggregate into the activities performed.

Construction activity had a peak in 2008 and decreased sharply after that. In relation to its spatial location, construction cannot be clearly identified in geographic terms. The use of area is temporary, their workers move to another construction site as soon as they have finished work in a building or flats. This affects not only the US, but also the ET, which may sometimes be included in residential consumption in the case of refurbishments.

### A.2.7 Energy sector

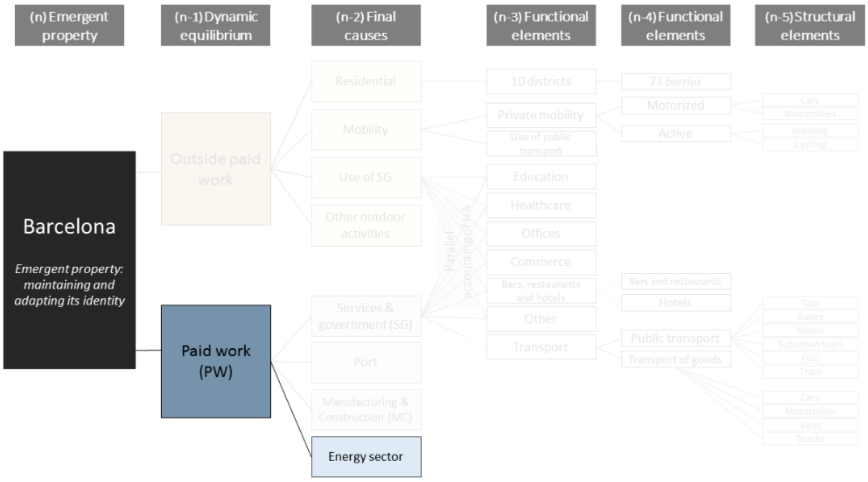


*Figure A-8 Situation of Energy sector in the general organization dendrogram of the system*

The representation of the energy sector in the end use matrix refers only to the amount of energy carriers used to generate energy carriers locally. – Figure A-9.

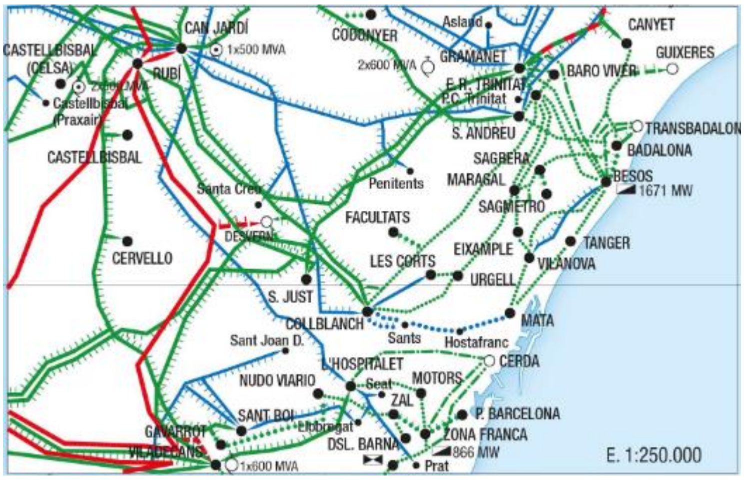


*Figure A-9 Map of the electric distribution system in and around Barcelona*

The only large generation plant located in the city is in the port, which also includes the import facilities for gas and oil products. We include an assessment of useful surface in relation to this element. The system of distribution of electricity includes main stations, substations and lines.

## A.3 Sources of data and data processing in relation to Human Activity

### A.3.1 General overview of sources of data

We used three main sources of data to cover Human Activity:

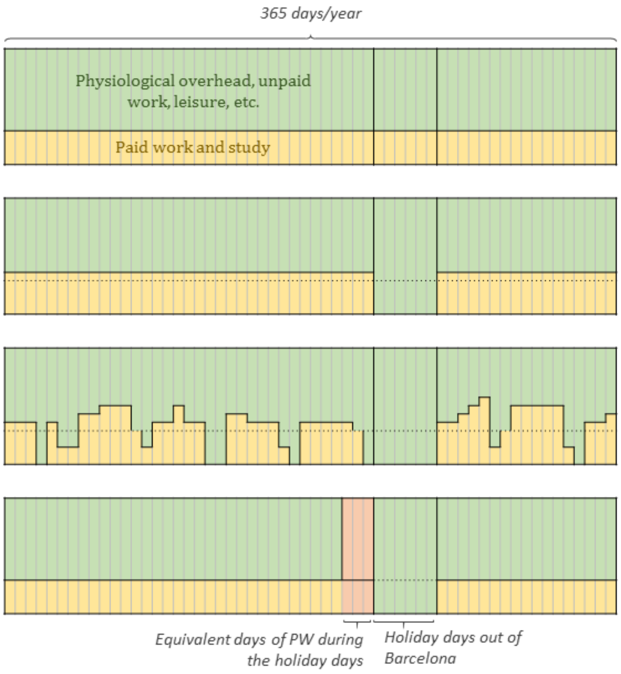
- Outside Paid Work: survey of time use in Catalunya (IDESCAT, 2012a),

- Mobility/transport: veh·km or number of trips in Barcelona, provided by Agència de l'Energia
- Paid Work statistics in Barcelona (Ajuntament de Barcelona, 2012a).

The survey of time use shows how citizens of Catalunya declare to spend their time during the 365 days of the year. The data is available as an average day, which is organized in diverse categories (age, region, gender, etc.). This survey refers to the use of time of the citizens of whole Catalunya. We are assuming this data is valid for Barcelona since the general values were very similar to those specific of the metropolitan area of Barcelona.

Data from this survey of time - divided by age groups (IDESCAT, 2012a)– was combined with the number of inhabitants per age group per *barrio*: *Age of the population by age group (5-year increments) and* barrio (Ajuntament de Barcelona, 2012a) for the calculations (A), (F) and (G). Since the survey of use of time is only considering citizens from 10 years old on, a guesstimate was made for the first group (0-10 years old), analyzing diverse statistics of the time spent at schools, and hypothesis on hours of sleep and play. In this way we have characterized differences over the age groups (0-9, 10-24, 25-44, 45-64, >65 years old) in each *barrio*. There was not enough available data to address other differences, e.g. employment status or gender. As started several times in this deliverable, this type of analysis makes only sense if carried out in participatory and in co-production with the user of the results, for example the local administrations that can indicate which attributes should be considered and identify potential sources of data and make ad-hoc survey when really needed.

The time of activities in the survey of time use were allocated with coefficients ($p_{jf}$) to all functions in the end-use matrix, detailed in Table A-7. These coefficients are broad estimates that were decided after research in reports on the different categories. Since the time use survey accounts the 365 days of the year and we are only accounting time happening in Barcelona, a strategy to allocate holidays and activities outside the city was made, shown in Figure A-10.



**Average day**

In holidays there's no study and no work. These hours would be included in the average of the rest of days.

This average day is the data from the survey of time use.

**Average day except holidays out of Barcelona**

In holidays there's no study and no work. These hours would be included in the average of the rest of days.

**Year-round variation of days**

In reality each day is diferent, but in this analysis we only want to know wha happens out and inside the city and this variaton is not relevant. It could be that all PW happens in other cities (daily commuting), or that due to PW some days in the year happen out of the city (congresses, meetings, etc.). Also, it could be true for other reasons (shopping, study, healthcare, etc.).

**Calculation**

In relation to the calculation, HA of activities out of PW and study are calculated for 365days minus the number of holiday days out of Barcelona and the equivalent days of PW during the holiday days (in orange). These HA are further divided out/inside Barcelona in the next steps.

*Figure A-10 Addressing the time of holidays out of Barcelona for Residents in HA*

The other elements have been calculated using other sources of data, but the results have been crosschecked with the data of the time use survey as well.

### A.3.2 The processing of data

This section details the calculations of hours of HA for each of the elements in the end-use matrix. The letter in parenthesis refers to the scheme given in Table A-1.

#### *(A) OPW/Residential*

Human activity for the residential sector for each *barrio* was calculated aggregating all the hours of the activities taking place inside the households from the survey of use of time divided by age groups in Catalunya (IDESCAT, 2012a) multiplied by the number of inhabitants per age group per *barrio*: *Age of the population by age group (5-year increments) and* barrio*. Official figures* (Ajuntament de Barcelona, 2012a). The data in the survey of time use includes the 365 days of the year, and since we are only accounting the activities happening inside the boundaries of the city, the holiday days outside the city (Observatori d'Empresa i Ocupació, 2012) have been subtracted. The actual number of holiday days is sure to be different across *barrios* and age groups, but an average value was used. Given that the time data is a year average and it includes paid work and study, activities that don't happen during holidays, this time had to be adjusted via the following equation.

]

$$HA_{RES_i} = \sum_j \sum_n inh_{in} \cdot t_{jn} \cdot p_{RESj} \cdot d_{BCN}$$

*Barrio* i [1…73]
Activities at home j
Age group n [0-9, 10-24, 25-44, 45-64, >65]

$inh_{in}$ number of inhabitants of *barrio* i and age group n [inh]
$t_{jn}$ average duration of the activity j for the group n [h/day]
$p_{RESj}$ share of the activity j that happens in the category residential [%]
$d_{BCN}$: days in the city (taking out holidays out of the city) [days/year]

### *(B) OPW/Mobility/Private mobility/motorized, OPW/Mobility/Use of PT/Taxi, PW/SG/Transport/Taxi and PW/SG/Transport/Transport of goods:*

These four functional elements contain different structural elements, some of them common in different elements:

*Table A-3 Structural elements in the functional elements related to transport in Barcelona*

| Functional element | Structural elements |
|---|---|
| **Private mobility motorized:** | cars, motorbikes, vans |
| **Taxi:** | cars |
| **Transport of goods:** | cars, vans, trucks and motorbikes |

Using the average values of speed and the average occupancy of the vehicles (Ajuntament de Barcelona, 2013), the veh·km run inside the boundaries of the city from *Agència de l'Energia* and the share allocated to the each category (private motorized, taxi users, taxi workers or transport of goods) we can obtain an estimate of HA for each one of them. Since the main source of data, veh·km, is divided per mode of transport and energy carrier and not per type of function, we had to define a factor allocating a share of these km to each category ($p_{fet}$). For example, in our source of data we have veh·km of diesel cars, gasoline cars and hybrid cars. But we cannot define how many of them are used by individuals (inside OPW/Mobility/Private mobility/Motorized), how many are used as taxis (PW/SG/Transport/Public transport) and how many are used by companies (PW/SG/Transport/Transport of goods). To estimate these differences we used information referring to the taxi fleet (IERMB, 2012b), the km run by taxis in Barcelona in 2012 (Ajuntament de Barcelona, 2013) and the ownership of vehicles: *Type of owner of passenger cars and motorbikes* (Ajuntament de Barcelona, 2012a). For those data sources referring only to typologies of vehicle without defining its function or the driver, any of the constituent components could be involved.

$$HA_f = \sum_t \sum_e \frac{x_{et} \cdot o_t \cdot p_{fet}}{v_t}$$

Type of vehicle t [cars, motorbikes, vans, trucks, etc.]
Energy carrier e [gasoline, gasoil]
Functional element f [OPW/Mobility/Private mobility/motorized, OPW/Mobility/Use of PT/Taxi, PW/SG/Transport/Taxi and PW/SG/Transport/Transport of goods]

$x_{et}$: distance run inside the boundaries of the city by the type of vehicle t using EC e [veh·km]
$o_t$: average occupancy per kind of vehicle [people/vehicle]
$v_t$: average speed per kind of vehicle [km/h]
$p_{fet}$: share of the km run allocated to the element, energy carrier and vehicle [%]

This approach leads to a potential double counting that is not controllable in the case of workers of the transport of goods. The workers using vehicles inside PW might or might not be registered in the same city, and even if they are registered in the city, they might have another principal activity other than transport, such as police, waste management, construction, repair and medical assistance. In order to minimize this double counting, half of this HA was subtracted from the category "Other" in SG (which includes the sub-category transport and storage), within the same larger category.

### *(C) OPW/Mobility/Private mobility/Active*

This assessment is based on: (i) the number of trips made inside the boundaries of Barcelona by residents and commuters (Ajuntament de Barcelona, 2013) and by tourists (Ajuntament de Barcelona and Barcelona Regional, 2017); (ii) the average speed per mode of transport and average distance per trip (Ajuntament de Barcelona, 2011). In relation to the behavior of tourists, the data from 2017 in number of trips per tourist per mode of transportation was assumed to be the same as in 2012, and so, a conversion factor was added (a). An equivalent number of weekdays was calculated, giving 322,4 days/year for residents and commuters (Transports Metropolitans de Barcelona, 2016), since in weekdays there is more mobility than in weekends, versus the 365 days/year for tourists.

$$\mathrm{HA}_{\mathrm{MOB}_{\mathrm{active}}} = \sum_{t}\sum_{c}\frac{n_{tc}\cdot x_t}{v_t}\cdot a\cdot d_c$$

Active mode of transport t [cycling, walking]
Constituent component c [residents + commuters, tourists]

$n_{tc}$: number of trips made inside the boundaries in the mode of transport t [trips/day]
$x_t$: average distance per trip per mode of transport [km/trip]
$v_t$: average speed per mode of transport t [km/h]
a: conversion factor:

- Residents + commuters: 1
- Tourists: Number of tourists 2012/number of tourists 2017

$d_c$: equivalent days for constituent component c (322,4days/year for residents + commuters and 365 for tourists)

### *(D) OPW/Mobility/Use of PT*

These assessments are based on: (i) the number of trips in public transport in 2012 (Ajuntament de Barcelona, 2013); (ii) the average speed per mode of transport and average distance per trip in 2008 (Ajuntament de Barcelona, 2011). Because the data on number of trips is given by the public transport companies, it includes all constituent components: residents, commuters and tourists. Also, the number of trips made was adjusted with the % of km of the network in Barcelona ($p_{PTBCN}$), since the network is larger than the city and some of the trips could have not been made in the city.

$$\mathrm{HA}_{\mathrm{PT}_{\mathrm{users}}} = \frac{n_{PT}\cdot x_{PT}\cdot p_{PTBCN}}{v_{PT}}$$

$n_{PT}$: number of trips made inside the boundaries in public transport [trips/year]
$x_{PT}$: average distance per trip in public transport in Barcelona [km/trip]
$v_{PT}$: average speed of public transport [km/h]
$p_{PTBCN}$: share of the km run allocated inside the boundaries in collective public transport [%]

### *(E) OPW/Use of SG/Education*

The amount of hours of students in Education has been calculated from the number of students in the city in the diverse levels: *Students Evolution by type of teaching* (Ajuntament de Barcelona, 2012a), multiplied by the number of hours per year of study per typology. These hours were estimated for each level using regulations and schedules of schools and universities. This data could be compared to the calculated from the time of education in the survey of time use (IDESCAT, 2012a) for residents, and statistics on the share of students per place of residence and study: *Displacements attracted and generated by schoolchildren and by university students* (Ajuntament de Barcelona, 2012a), which afterwards will be used in the constituent component calculation.

### *(F) OPW/Use of SG/Healthcare, OPW/Use of SG/Offices, OPW/Use of SG/Commerce, OPW/Use of SG/Hotels, OPW/Use of SG/Bars and restaurants and OPW/Use of SG/other*

These categories are calculated by adding the HA from the three HA of constituent components calculated separately.

First of all, we have the time in service and government activities for residents as users, via hypothesis on the share of the related activities in the survey of use of time, detailed in Table A-7 (at the end of this Appendix)Table A-7. The calculation is similar to that on (A), but since these activities might or might not take place in Barcelona, a calculation on the share of the human activity taking place in Barcelona has to be included (Ajuntament de Barcelona, 2012b). This time is approached in two complementary ways, not taking into account: (i) the days of holidays outside of the city (with $d_{BCN}$) and (ii) the activities that are carried out in the metropolitan area (with $p_{BCNf_{residents}}$).

$$\mathrm{HA}_{\mathrm{BCNf}_{\mathrm{residents}}} = \mathrm{p}_{\mathrm{fBCN}_{\mathrm{residents}}} \sum_{i} \sum_{j} \sum_{n} \mathrm{inh}_{\mathrm{in}} \cdot \mathrm{t}_{\mathrm{jn}} \cdot \mathrm{p}_{\mathrm{jf}} \cdot \mathrm{d}_{\mathrm{BCN}}$$

Barrio i [1…73]
Activities of the time use survey j
Functional element f [healthcare, offices, commerce, bars and restaurants, etc.]
Age group n [0-9, 10-24, 25-44, 45-64, >65]

$inh_{in}$ number of inhabitants of barrio i and age group n [inh]
$t_{jn}$ average duration of the activity j for the group n [h/day]
$p_{jf}$ share of the time of the activity of the time use survey j that happens in the element f [%]
$p_{fBCNresdients}$ share of the time of the element f happening in Barcelona by residents [%]
$d_{BCN}$: days in the city (taking out holidays out of the city) [days/year]

Then, dividing these estimates by the total number of inhabitants in Barcelona, we can know how much time is used per capita in each functional element. We consider these values valid for all the residents in AMB (including potential commuters). Then, this value is multiplied by the number of residents in AMB outside BCN $(\mathrm{inh}_{\mathrm{AMB}} - \mathrm{inh}_{\mathrm{BCN}})$ and the share of the human activity taking place in Barcelona $(\mathrm{p}_{\mathrm{BCNf}_{\mathrm{commuters}}})$ in order to know the HA from commuters devoted to these activities in Barcelona. In conclusion,

$\mathrm{p}_{\mathrm{BCNf}_{\mathrm{commuters}}}$ was estimated by element f in base to the time out of the municipalities where commuters live (IDESCAT *et al.*, 2012).

$$\mathrm{HA}_{\mathrm{BCNf}_{\mathrm{commuters}}} = \frac{\mathrm{HA}_{\mathrm{f}_{\mathrm{residents}}}}{\mathrm{inh}_{\mathrm{BCN}} \cdot \mathrm{p}_{\mathrm{BCNf}_{\mathrm{residents}}}} \cdot (\mathrm{inh}_{\mathrm{AMB}} - \mathrm{inh}_{\mathrm{BCN}}) \cdot \mathrm{p}_{\mathrm{BCNf}_{\mathrm{commuters}}}$$

Functional element f [healthcare, offices, commerce, bars and restaurants, etc.]

$\mathrm{HA}_{\mathrm{BCNfcommuters}}$: time spent by commuters in Barcelona in the use or consumption of the functional element f
$\mathrm{HA}_{\mathrm{fresidents}}$: time spent by residents in the use or consumption of the functional element f
$\mathrm{inh}_{\mathrm{BCN}}$: inhabitants Barcelona (residents)
$\mathrm{inh}_{\mathrm{AMB}}$: inhabitants Metropolitan Area
$\mathrm{inh}_{\mathrm{AMB}}$-$\mathrm{inh}_{\mathrm{BCN}}$: inhabitants Metropolitan Area out of Barcelona (potential commuters)
$\mathrm{p}_{\mathrm{BCNfresidents}}$: share of the time of residents inside Barcelona [%]
$\mathrm{p}_{\mathrm{BCNfcommuters}}$: share of the time of commuters inside Barcelona [%]

In relation to tourists, we have data on the type and number of tourists, and average days of stay for 2012 (excursionists, overnight in hotels and overnight in other) (Direcció de Serveis de Mobilitat and Direcció Operativa de Turisme i Esdeveniments, 2014). From this data, we generated profiles of time use , with the share of principal motivation to travel (Direcció de Serveis de Mobilitat and Direcció Operativa de Turisme i Esdeveniments, 2014). The Human Activity of Tourists is divided in 6 categories: (i) hotels, (ii) bars and restaurants, (iii) other (arts, sports, entertainment, etc.), (iv) mobility, (v) other outdoor activities; and (v) paid work. In in this case the workers are not working for companies in Barcelona and their hours do not sum to the hours of PW, they are accounted as HA of Use of Services and Government (Hotels, Offices and Other). This hypothesis could be adjusted depending on the goal of the analysis. In the case of excursionists, who don't spend the night in the city, the time of hotels of the profile of time use won't be included. Table A-4 illustrates in an overview the estimates of time use for tourists.

*Table A-4 Estimates of time use profiles of tourists by motivation of travel (measured in hours/day)*

| | | Time use profiles [h/day] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Total | | | Leisure | | | | |
| Principal motivation of travel | 2014 | Mobility | Hotels | Shopping | Bars& rest. | Other (Arts, sports, etc.) | Other outdoor act. | PW |
| Holidays, leisure | 62.30% | 1 | 9 | 3 | 3 | 6 | 2 | 0 |
| Professional | 24.10% | 1.1 | 9 | 1 | 3 | 1 | 0.9 | 8 |
| Others | 13.60% | 1.5 | 9 | 2 | 3 | 6.5 | 2 | 0 |

### *(G) OPW/Other outdoor activities*

Other outdoor activities (OOA) refer to activities happening in the public space but not accounted as mobility or paid work, for example: going for a walk, running, playing in a park, etc. This time is a significant amount and it has to be taken into account. The calculation is divided in the three constituent components. First of all, the calculation method for residents is similar to that to (A) for residential, using the Survey of Time Use.

$$\mathrm{HA_{OOA}} = \sum_{i}\sum_{j}\sum_{n} \mathrm{inh_{in}} \cdot \mathrm{t_{jn}} \cdot \mathrm{p_{RESj}} \cdot \mathrm{d_{BCN}}$$

*Barrio* i [1…73]
Activities in Other outdoor activities j
Age group n [0-9, 10-24, 25-44, 45-64, >65]

$\mathrm{inh_{in}}$ number of inhabitants of *barrio* i and age group n [inh]
$\mathrm{t_{jn}}$ average duration of the activity j for the group n [h/day]
$\mathrm{p_{RESj}}$ share of the activity j that happens in the category residential [%]
$\mathrm{d_{BCN}}$: days in the city (taking out holidays out of the city) [days/year]

Then, the approach for commuters is similar to that of (F), we are considering the average value per resident as valid per all the Metropolitan Area. Only that the value of $\mathrm{p_{BCNOOA_{commuters}}}$ is found using mobility data. This is, a trip for OOA reasons will take the same time of OOA activity either for residents than commuters.

$$\mathrm{HA_{BCNOOA_{commuters}}} = \mathrm{HA_{OOA_{residents}}} \cdot \frac{\mathrm{disp_{OOAcommuters}}}{\mathrm{disp_{OOAresidents}}}$$

Functional element f [healthcare, offices, commerce, bars and restaurants, etc.]

$\mathrm{HA_{BCNOOAcommuters}}$: time spent by commuters in Barcelona in Other Outdoor Activities (OOA)
$\mathrm{HA_{OOAresidents}}$: time spent by residents in OOA
$\mathrm{disp_{OOAcommuters}}$: number of displacements (to OOA) to Barcelona from people living in AMB outside Barcelona
$\mathrm{disp_{OOAcommuters}}$: number of displacements (to OOA) from and to Barcelona from people living in Barcelona

The approach for tourists uses the same logic as the diverse activities explained in (F).

### *(H) PW/SG/(Education, Healthcare, Offices, Commerce, Hotels, Bars and restaurants, Other), PW/Manufacturing and Construction and PW/Energy Sector*

The calculations of work HA for a large amount of the categories in PW inside Services and Government, Manufacturing and Construction and the Energy Sector share the same logic that requires considering the presence of hours of work that are not officially registered in the available statistics. In fact, when comparing the hours from the data of official statistics ($\mathrm{HA_{PWstatistics}}$) per sub-sector we find values not consistent with those resulting from the declared time of paid work in the survey of human time ($\mathrm{HA_{PW_{survey}}}$). This discrepancy flags the existence of working time declared by the citizens in the survey but not registered by official statistics: a sign of the existence of shadow economy. Even though the shadow economy is not considered in government statistics it is relevant to the metabolism of the city. The energy consumption of these activities is already accounted in the statistics.

The human activity of residents who work- $\mathrm{HA_{PWresidentssurvey}}$ - was calculated from the survey of human time, similarly to the one in the category HH. This human activity takes place either inside or outside the city and it refers only to residents.

$$\mathrm{HA}_{\mathrm{PW}_{\mathrm{residentssurvey}}} = \sum_{\mathrm{i}} \sum_{\mathrm{n}} \mathrm{inh}_{\mathrm{in}} \cdot \mathrm{t}_{\mathrm{PWn}} \cdot 365$$

Barrio i [1…73]
Age group n [0-9, 10-24, 25-44, 45-64, >65]

$\mathrm{inh}_{\mathrm{in}}$ number of inhabitants of barrio i and age group n [inh]
$\mathrm{t}_{\mathrm{PWn}}$ average duration of paid work time for the group n [h/day]

To know how much the share of these hours of work inside the city, we use the information that 74.6% of the Barcelona's residents work in BCN. Then, to calculate the total time of paid work in Barcelona - from $\mathrm{HA}_{\mathrm{PW}_{\mathrm{survey}}}$ - we use the information that 49.6% of the workers in Barcelona are residents (both data from Ajuntament de Barcelona, 2012a). $\mathrm{HA}_{\mathrm{PW}_{\mathrm{survey}}}$ is the estimate of the final $\mathrm{HA}_{\mathrm{PW}}$, including shadow economy and both residents and commuters.

$$\mathrm{HA}_{\mathrm{PW}_{\mathrm{survey}}} = \mathrm{HA}_{\mathrm{PW}_{\mathrm{residentssurvey}}} \cdot \frac{74.6\% \text{ BCN residents work in BCN}}{49.6\% \text{ of the workers in BCN live in BCN}}$$

On the other side, $\mathrm{HA}_{\mathrm{PW}_{\mathrm{statistics}}}$ is calculated by using the number of workers per sub-sector in Barcelona ($x_f$) (Ajuntament de Barcelona, 2012) and the average hours worked in the four big sub-sectors in Catalunya in 2012 ($t_s$) (IDESCAT, 2012a), only considering the working days.

$$\mathrm{HA}_{\mathrm{PW}_{\mathrm{statistics}}} = \sum_{\mathrm{f}} \mathrm{x}_{\mathrm{f}} \cdot \mathrm{t}_{\mathrm{s}} \cdot \mathrm{d}_{\mathrm{w}}$$

Sub-sector f [manufacturing and construction, education, healthcare, commerce, offices, hotels, bars and restaurants, energy sector]
Sector s [agriculture, manufacturing, construction, services]

$x_f$: number of workers for the sub-sector f [workers]
$t_s$: average hours worked per day in the sector s [h/day]
$d_w$: working days in a year [days/year]

The amount of HA in PW coming from the shadow economy, $\mathrm{HA}_{\mathrm{PW}_{\mathrm{to\ allocate}}}$ is calculated by the difference of these two $\mathrm{HA}_{\mathrm{PW}}$, official and declared:

$$\mathrm{HA}_{\mathrm{PW}_{\mathrm{survey}}} - \mathrm{HA}_{\mathrm{PW}_{\mathrm{statistics}}} = \text{shadow HA} = \mathrm{HA}_{\mathrm{PW}_{\mathrm{to\ allocate}}}$$

The criterion for the allocation of the shadow HA by sub-sectors is made with the data of % of the black GDP for each sub-sector f at an European level ($\mathrm{p}_{\mathrm{blackGDP}_{\mathrm{f}}}$), in the report *The shadow economy in Europe 2013* (Schneider, 2013).

$$\mathrm{HA}_{\mathrm{PW}_{\mathrm{to\ allocate}}} \cdot \mathrm{p}_{\mathrm{blackGDP}_{\mathrm{f}}} = \mathrm{HA}_{\mathrm{PWf}_{\mathrm{black}}}$$

Finally, $\mathrm{HA}_{\mathrm{PW}_{\mathrm{f}}}$ is the sum of the calculated from statistics and the one from the black economy for each sub-sector. In some cases this extra time is a large share:

$$\mathrm{HA}_{\mathrm{PW}_{\mathrm{f}}} = \mathrm{HA}_{\mathrm{PWf}_{\mathrm{statistics}}} + \mathrm{HA}_{\mathrm{PWf}_{\mathrm{black}}}$$

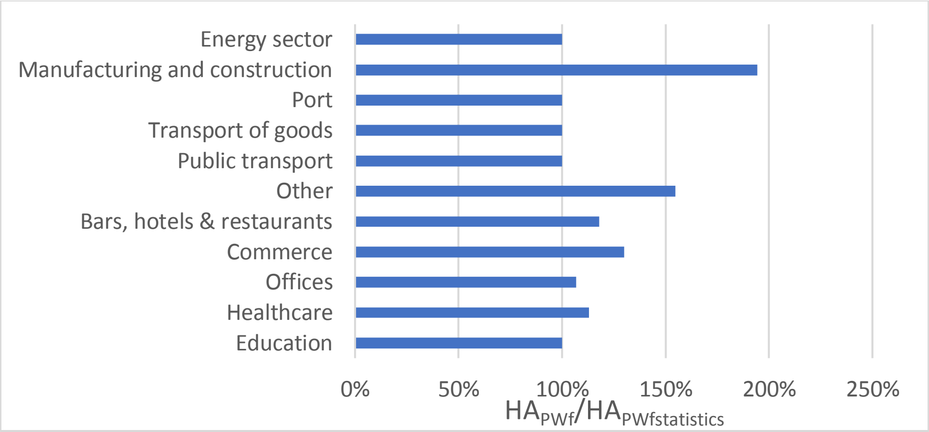


*Figure A-11 Estimation of the importance of shadow economy in human activity of Barcelona over different Paid Work categories*

As indicated in Figure A-11, the sector of construction is the sector where, by far, we should expect a greater underestimation of work activity in the official statistics due to the existence of the shadow economy.

Another important aspect to be considered to avoid double counting is the assessment of working hours in the category labelled "Other" within Services and Government. It includes the workers in the category "*Transport and storage*" (*H. Transports i emmagatzematge*), and so, the workers in Public Transport, Transport of goods and the Port. In order to avoid double counting, the HA from Public Transport, Port and half from the transport of goods were subtracted. Only half of the hours from Transport of Goods are subtracted, due to the problem of the long range of the transport and that not necessarily those workers driving vehicles in the city are working in activities directly related to transport.

### *(I) PW/SG/Transport/Collective public transport*

The work time for collective public transport (regional train, buses, metro, tram) was calculated from the number of workers in the different companies ($x_t$) (IERMB, 2012b; Transports Metropolitans de Barcelona, 2012; Renfe, 2014) and the average hours worked in the services sector in Catalunya in 2012 (IDESCAT, 2012b). This assessment only considers working days and applies to the share of km made inside the city (provided by AEB). This value had to be subtracted from the "others" HA (category *H: Transports i emmagatzematge*).

$$\mathrm{HA_{CPTW}} = \sum_{t} x_t \cdot t_{SG} \cdot d_w \cdot p_{tBCN}$$

Mode of collective public transport t [metro, train, tram, fgc]

$x_t$: number of workers for the mode t [workers]
$t_{SG}$: average hours worked per day in services [h/day]
$d_w$: working days in a year [days/year]
$p_{tBCN}$: share of the km run allocated inside the boundaries in the mode t [%]

### *(J) PW/Port*

The values for number of workers are available in documents of the Agència Portuaria (Port de Barcelona, 2012, 2017). This element of the system is already included in the overall assessments referring to higher level categories in the statistics. Assessing the working time in the port using these bottom-up data generates a problem of potential double counting because the port includes workers from different sectors - the primary (marginal), secondary and tertiary sector. Therefore these hours were subtracted to the category SG "Other" (which includes the category *H: transport and storage*, *H: Transports i emmagatzematge*).

## A.3.3 The allocation of Human Activity of constituent components (who is doing what)

As discussed in Section 4.2.2, when assessing quantities of human activity it is not only important to assess quantity of hours/year in relation to the categories of functional activity (*what* it is done and *how*), but also to assess constituent components: to whom belongs to. This information makes it possible to understand the *why*, the final cause of the functional activity. As discussed in Section 3, in Barcelona we identified three constituent components: residents, commuters and tourists (Figure A-12).

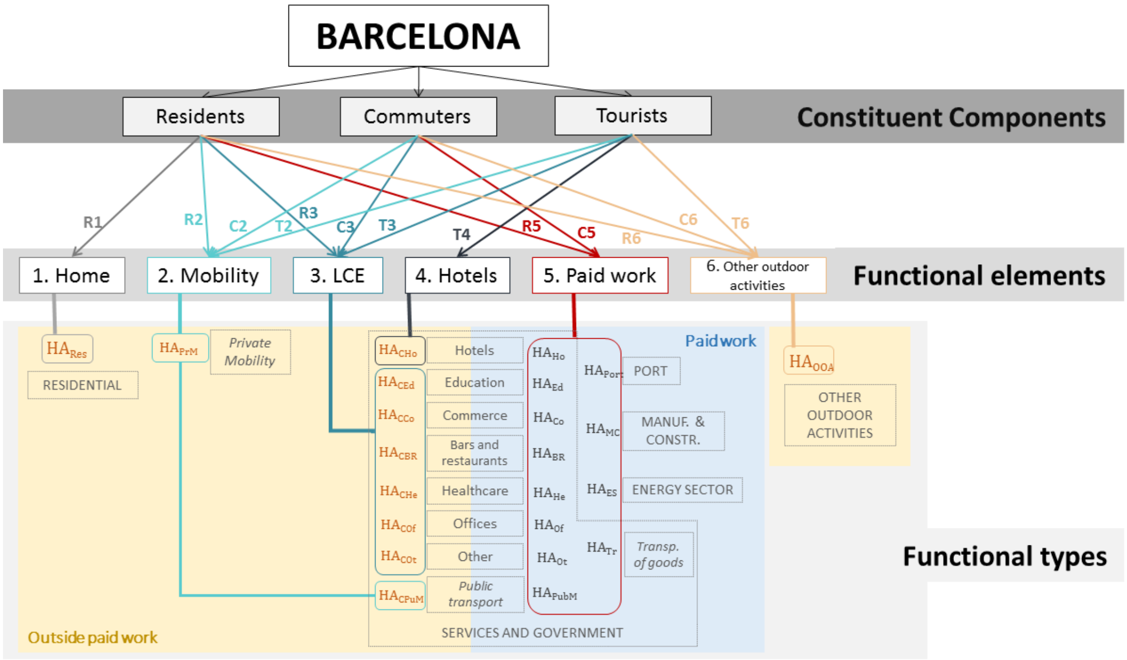


*Figure A-12 Classification and relationship of human activities per constituent component and functional elements*

The discussion of how to establish a relation over the two sets of categories: (i) the sources of hours of human activity (constituent components); and (ii) the end-use of human activity (functional elements) is given in Section 4.2.2. Here we describe the strategy used for the calculation starting from the scheme given in Table A-5.

*Table A-5 Scheme of references to the calculation strategies of HA for functional elements and the constituent components involved*

| | | | HA<br>h | Constituent components |
|---|---|---|---|---|
| OUTSIDE PAID WORK | **RESIDENTIAL** | | | |
| | | 73 barrios | **A** | R |
| | **MOBILITY** | | | |
| | | Private motorized | **B** | R+C+T |
| | | Active | **C** | |
| | | Taxi | **B** | |
| | | Collective public transp. | **D** | |
| | **USE OF SG** | | | |
| | | Education | **E** | R+C |
| | | Healthcare | **F** | |
| | | Offices | | |
| | | Commerce | | R+C+T |
| | | Hotels | | T |
| | | Bars and restaurants | | R+C+T |
| | | Other | | |
| | **OTHER OUTDOOR ACTIVITIES** | | **G** | R+C+T |
| PAID WORK | **SERVICES & GOVERNMENT** | | | |
| | | Education | **H** | R+C |
| | | Healthcare | | |
| | | Offices | | |
| | | Commerce | | |
| | | Hotels, bars and restaurants | | |
| | | Other | | |
| | | Taxi | **B** | |
| | | Collective public transp. | **I** | |
| | | Transport of goods | **B** | R+C+other |
| | **PORT** | | **J** | R+C |
| | **MANUFACT. & CONSTRUCT.** | | **H** | |
| | **ENERGY SECTOR** | | | |

*Table A-6 Allocation of human activity coupling: (i) constituent component; and (ii) functional elements*

| Functional element | Related HA calc. | Constituent component | Allocation strategy |
|---|---|---|---|
| **1. Home** | (A) | R1: Residents | All time in residential |
| **2. Mobility** | (B), (C), (D) | R2: Residents<br>C2: Commuters | Hypothesis: share of time of residents and commuters is the same as share of trips: 79.3% of the trips are of residents (IERMB, 2012a) |
| | | T2: Tourists | Calculation of HA from the share of trips of tourists (Ajuntament de Barcelona and Barcelona Regional, 2017). |
| **3. LCE** | | R3, C3, T3 | |

| | | | |
|---|---|---|---|
| Education | (E) | Residents Commuters | Share of students in Barcelona by place of residence (Ajuntament de Barcelona, 2012a) |
| Healthcare, offices, commerce, Bars and restaurants and other | (F) | Residents, commuters, tourists | Already accounted separately in (F) |
| **4. Hotels** | (F) | T4: Tourists | All time in the consumption side of hotels |
| **5. Paid work** | (B), (H), (I), (J) | R5: Residents<br>C5: Commuters | Amount of human activity in paid work.<br>% of workers in Barcelona by place of residence (Ajuntament de Barcelona, 2012a) |
| **6. Other outdoor activities** | (G) | R6: Residents<br>C6: Commuters<br>T6: Tourists | Already accounted separately in (G) |

Below we provide a detailed explanation organized per functional category.

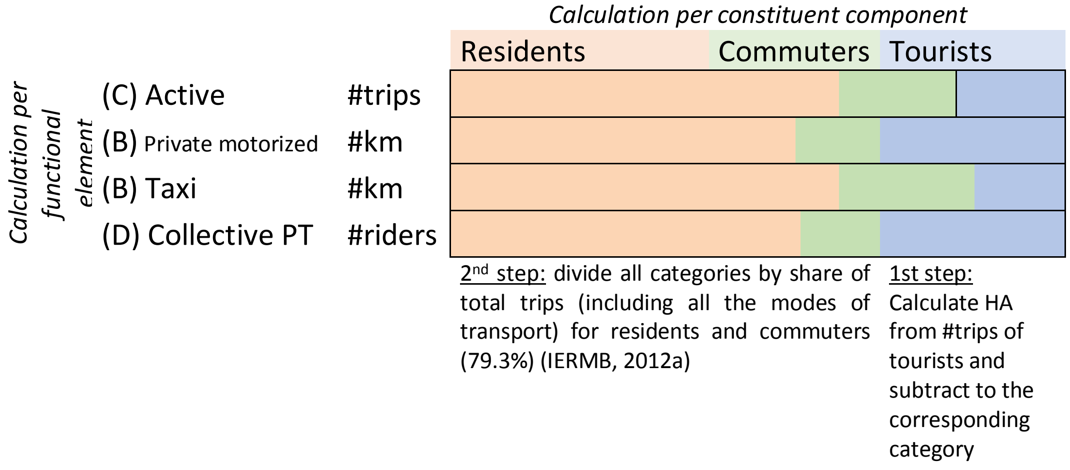
### *Home*

The functional element "home" coincides with the category Residential, and it only includes the hours of residents, as already explained in (A).

### *Mobility*

In order to distribute the hours spent in mobility as users, the following two steps were made:

First, the mobility time of tourists was calculated based on the number of trips: *Estimació de la mobilitat turística segons modes de transport (desplaçaments/dia)* (Ajuntament de Barcelona and Barcelona Regional, 2017). A fraction of it was already calculated in relation to active mobility (C).



2nd step: divide all categories by share of total trips (including all the modes of transport) for residents and commuters (79.3%) (IERMB, 2012a)

1st step: Calculate HA from #trips of tourists and subtract to the corresponding category

*Figure A-13 Calculation of the breakdown of human activity in Mobility*

$$HA_{f_{tourists}} = \frac{tou_{2012}}{tou_{2017}} \sum_{t \in f} \frac{n_{ttourists} \cdot x_t}{v_t}$$

Mode of transport t [walking, cycling, car, etc.]
Functional element f [active, private motorized, taxi, collective PT]

$n_{ttourists}$: number of trips made inside the boundaries in the mode of transport t by tourists [trips/day]
$x_t$: average distance per trip per mode of transport [km/trip]

$v_t$: average speed per mode of transport t [km/h]
$tou_{2012}$: number of tourists in 2012
$tou_{2017}$: number of tourists in 2017

After having subtracted the HA from tourists, the rest of HA of the categories (active, motorized, taxi and collective PT) was multiplied by the same factor: the % of the trips made by residents in Barcelona (79.3%) and commuters (20.7%) from the survey of daily mobility, which includes only people living in the RMB (IERMB, 2012a).

The analysis of mobility data compared to paid work gave non coincident conclusions. The large amount of commuting due to paid work that would be generated according to the paid work statistics (half of the workers in Barcelona are commuters) does not reflect on the mobility data, since less commuting is declared in EMEF.

#### *LCE: Leisure, Commerce and Education*

This category was already calculated separately in most of the sub-sectors that are included (healthcare, offices, commerce, bars and restaurants and other) – as explained in (F). In the case of Education a statistic on the share of the origin of the students at school and university level that study in Barcelona: *Displacements attracted and generated by university studies and by schoolchildren* (Ajuntament de Barcelona, 2012a) has been used to separate the total value, calculated in (E) between residents and commuters.

#### *Hotels*

The functional element Hotels maps on the working time in Hotels in the SG element, and the hours of activities of tourists in hotels - as explained in (F).

#### *Paid work*

A statistic on the share of the origin of the people that work in Barcelona was used: *Relationship residence-place of work covered by social security* (Ajuntament de Barcelona, 2012a), to divide the sum of the $HA_{PW}$, which includes the values explained in (B), (H), (I), (J).

#### *Other outdoor activities*

The functional element Other outdoor activities was already calculated separately from the different constituent components- as explained in (G).

## A.4 Data sources and data processing in relation to Useful Surfaces

The following sections explain the data sources and the calculation for areas, the Useful Surface of Barcelona. As discussed in Section 4, area can refer to two different typologies, each end-use has its related typology indicated in Table 4-8 in Section Assessing quantities of areas used (Built Environment) 4.2.3, summarized in the category Useful Surfaces: (i)

Building Use – internal area of building measured in m$^2$ of floors in buildings (this assessment implies considering 3D for dealing with multi-story buildings); (ii) Land Use within the area of the city limited by the boundary, in a 2D sense. Land Use data for 2012 comes from the statistical website of the Ajuntament de Barcelona: *Surface districts and* barrios *to aggregate land use* (Ajuntament de Barcelona, 2012a).

### A.4.1 The processing of data

#### *(J) OPW/Residential:*

The total area of households in use per *barrio* was calculated from the number of households in Opendata BCN: *Average occupancy per permanent addresses* (Ajuntament de Barcelona, 2016b) and the total number and area of households provided by Agència de l'Energia. The process to get the total BU is to calculate the average area of households for each barrio and then multiply by the effective number of households in use.

Barrio i [1…73]

$$\mathrm{BU}_{\mathrm{Res}_\mathrm{i}} = \frac{\mathrm{BU}_{\mathrm{ResTotal}_\mathrm{i}}}{\mathrm{HH}_{\mathrm{Total}_\mathrm{i}}} \cdot \mathrm{HH}_{\mathrm{InUse}_\mathrm{i}}$$

$\mathrm{BU}_{\mathrm{Resi}}$: building use for households for *barrio* i [m$^2$]
$\mathrm{BU}_{\mathrm{Resi}}$: total building use for apartments/houses barrio i [m$^2$]
$\mathrm{HH}_{\mathrm{Totali}}$: total number of apartments/houses in barrio i
$\mathrm{HH}_{\mathrm{InUsei}}$: total number of households in use in barrio i

#### *(K) OPW/Mobility/Private mobility and PW/SG/Transport/Transport of goods:*

The area considered to calculate the metabolic density of energy spent in mobility is that of the network of roads and parking areas that are dedicated to vehicles, estimated from the mobility data of 2012 (Ajuntament de Barcelona, 2013). Half of this area was allocated to Motorized Private Mobility and the other half to Transport of Goods in Services and Government. Again in this illustrative example we are taking these allocation decisions on our own. But in real applications this type of decisions should depend on: (i) the purpose of the analysis; and (ii) participatory processes. Taxis are in the public transport category and have no area allocated. In the case of active mobility, the BU is the one devoted to pedestrians, coming from the same data source (Ajuntament de Barcelona, 2013). The area occupied by bike lanes is not included in this assessment because there wasn't available data.

#### *(M) PW/SG/(education, healthcare, offices, commerce, hotels, bars and restaurants, other) and PW/Manufacturing and Construction*

Data about Building Use (km$^2$) was provided by AEB and Opendata BCN (Ajuntament de Barcelona, 2016b). However, in the case of manufacturing and construction it only includes factories, and, as mentioned earlier, it does not include of the area of open construction sites. Also, we could not estimate the area of buildings which are under refurbishment. It is an important missing piece of information because construction has a significant weight in terms of HA and VA.

### *(N) PW/Port*

The area occupied by the port can be found in documents of the Agència Portuaria (Port de Barcelona, 2017, 2018). Data on the Port are included in other higher level categories in conventional statistics, with workers belonging to different sectors. The same problem is found when mapping its size in spatial terms. Its area belongs partially to the *La Marina del Prat Vermell barrio* and partially to another municipality El Prat de Llobregat, and so not included in the statistics of Barcelona. To avoid double counting the area of LU of the port inside Barcelona (estimated from bottom-up sources) was subtracted from the area of the LU manufacturing of the *La Marina del Prat Vermell barrio*.

### *(O) PW/Energy Sector:*

The area of LUs of the energy sector was found in Agència Portuaria GIS website, which includes the data from the catastro (Port de Barcelona, 2018). This value was subtracted from the estimate of the LU of the Port.

## A.5 Data sources and data processing in relation to Energy Carrier Throughputs

### A.5.1 The processing of data

### *(P) OPW/Residential*

The total energy carrier consumption (based on quantitative assessment aggregating kWh of electricity and MJ of heat) for the 73 *barrios* was provided by the AEB for the year 2012 ($\mathrm{ET}_{\mathrm{RES}_{12\mathrm{i}}}$). So we had to develop a strategy to breakdown the assessment to the two components of electricity and heat.

Data on energy consumption divided per energy carrier e (heat and electricity) for the 73 *barrios* was available from a simulation from the year 2014 ($\mathrm{ET}_{\mathrm{RES}_{\mathrm{ei}14}}$) made by Agència de l'Energia. Data on electricity and heat consumption were available at a Barcelona level for both 2012 and 2014 ($\mathrm{ET}_{\mathrm{RES}_{\mathrm{e}14}}$, $\mathrm{ET}_{\mathrm{RES}_{\mathrm{e}12}}$), and so two conversion factors, one for electricity and other for heat, could be calculated.

Energy carrier e [electricity, heat]

$$\frac{\mathrm{ET}_{\mathrm{RES}_{\mathrm{e}12}}}{\mathrm{ET}_{\mathrm{RES}_{\mathrm{e}14}}} = \mathrm{p}_{\mathrm{RES}_{\mathrm{e}14\to12}}$$

$\mathrm{ET}_{\mathrm{RESe12}}$: Consumption for the year 2012 in the residential sector for Barcelona for energy carrier e

$\mathrm{ET}_{\mathrm{RESe14}}$: Consumption for the year 2014 in the residential sector for Barcelona for energy carrier e

$\mathrm{p}_{\mathrm{RESe14}\to12}$: conversion factor from 2014 to 2012 for energy carrier e

Using these conversion factors, we converted the data per barrio referring to 2014 to the assessments in 2012 assuming that all the *barrios* had the same variation.

$$\mathrm{ET}_{\mathrm{RES}_{\mathrm{ei12}}} = \mathrm{p}_{\mathrm{RES}_{\mathrm{e14}\rightarrow 12}} \cdot \mathrm{ET}_{\mathrm{RES}_{\mathrm{ei14}}}$$

$\mathrm{ET}_{\mathrm{RESe12i}}$: Consumption of energy carrier e for the year 2012 in the residential sector for the *barrio* i

$\mathrm{p}_{\mathrm{RESe14}\rightarrow 12}$: conversion factor of energy carrier e from 2014 to 2012

This assessment done in this way has maintained the congruence with the overall value of ET consumption for electricity and heat at the level of whole Barcelona.

The comparison between the aggregated ET per barrio from the calculations ($\mathrm{ET}_{\mathrm{RES}_{\mathrm{ei12}}}$) and the statistics ($\mathrm{ET}_{\mathrm{RES}_{\mathrm{i12}}}$) – Figure A-14- shows larger differences, which are more relevant at lower $\mathrm{ET}_{\mathrm{RES}_{\mathrm{i12}}}$, with only 3 *barrios* with a difference over ±10%.

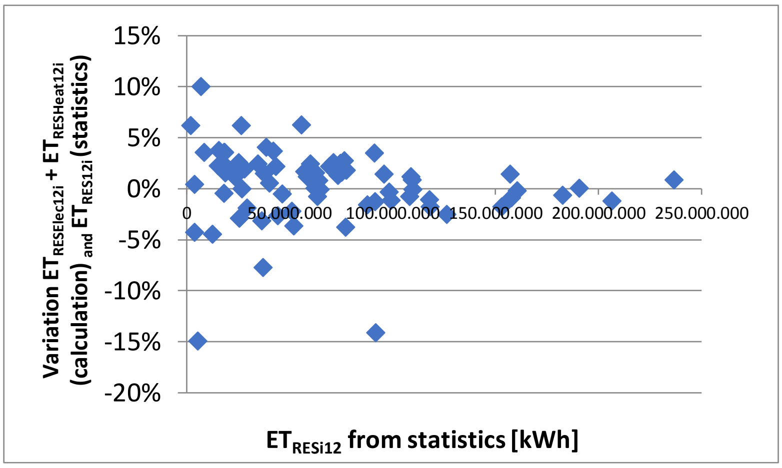


*Figure A-14 Comparison of calculation and statistics ET by barrios from 2012.*

### *(Q) OPW/Mobility/Private mobility, PW/SG/Transport*

The ET allocated to transport and mobility had two parts: the one due to the consumption of vehicles and the one due to lighting. Thus, active modes do not have exosomatic energy in their direct consumption, but they are going to have a share of the lighting allocated to it.

The first part of ET was calculated using the number of km run by type of vehicle and energy carrier in 2013 and values of fuel used per km per type of vehicle and energy carrier provided by the Agència de l'Energia de Barcelona. Since some cars and motorbikes are used in private business, public services or as taxis, we had to decide a criterion of allocation of the km between these categories ($\mathrm{p}_{\mathrm{fet}}$). We adopted the same criterion used for the allocation of hours of human activity in (B). $\mathrm{p}_{\mathrm{fet}}$ for cars used as taxis, was based on the assessment of the km run by taxis in Barcelona in 2012 (Ajuntament de Barcelona, 2013) and the number and type of vehicles in the fleet of taxis was used to estimate the allocation for each energy carrier: diesel, gasoline and natural gas (IERMB, 2012b). For the other cars and motorbikes that are used in the PW sector (e.g. delivery, police, etc.) we used the data on cars and motorbikes owned by individuals and companies: *Type of owner of passenger cars and motorbikes* (Ajuntament de Barcelona, 2012a).

$$\mathrm{ET_e} = \sum_{\mathrm{t \in e}} \mathrm{x_{et}} \cdot \mathrm{c_{et}} \cdot \mathrm{p_{fet}}$$

Type of vehicle t [cars, motorbikes, bus, tram, metro, etc.]
Energy carrier e [gasoline, gasoil, electricity, natural gas, etc.]

$x_{et}$: distance run inside the boundaries of the city by the type of vehicle t and energy carrier e [veh·km]
$c_t$: energy consumption per km [MJ/km]
$pf_{et}$: share of the km run by vehicle t with energy carrier e allocated to the category f [%]
322,4: equivalent days [days/year]

Electricity consumption of public lighting was available in the Report *L'energia a* Barcelona (Observatori de l'Energia de Barcelona, 2013). It was allocated in function to the km run per each mode of transport.

### *(R) PW/SG/(education, healthcare, offices, commerce, hotels, bars and restaurants, other)*

The aggregated (electricity + heat) energy consumed and the BU for most of the sub-sectors in 2012 was provided by AEB. In the case of education and healthcare, data on energy intensity (kWh/m$^2$) from a report from 2008 was used (Ajuntament de Barcelona, 2011) with the BU from Opendata BCN (Ajuntament de Barcelona, 2016b). This data does not provide a defined mix of quantity of energy of different forms: electricity and heat. For this reason we had to estimate the share of thermal energy and electricity looking at sectorial reports on these type of consumption referring to studies carried out in Barcelona and Spain (INDESCAT, 2012; Gauchia Legal, 2013; Nuñez-Cacho del Águila, 2013; PyME Energy CheckUp, 2013, 2014, 2015) to fill the two categories of energy qualities: $ET_{elec}$ and $ET_{heat}$. The category "Other" was used to fit the bottom-up data to the top-down data for services from AEB.

### *(S) PW/Port*

The values for the energy consumption at the port were taken from a paper analyzing its GHG emissions for the year 2008 (Villalba and Gemechu, 2011). The quantity of EC is directly given for the land-based activities, whereas the emissions from the vessels were calculated from the tons of $CO_2$ of their movements inside a boundary of 1 nautical mile distance from the port. The energy from land-based activities was subtracted from ET in CM in order to avoid double counting.

### *(T) PW/Manufacturing and Construction*

Electricity and natural gas consumption in Manufacturing and Construction was provided by ICAEN, with the other EC negligible (Ajuntament de Barcelona, 2011). The ET from the port was subtracted to it to avoid double counting.

### *(U) PW/Energy sector*

The values for ET in the energy sector were those used for the Deliverable 4.1 for the MAGIC-Nexus project (Di Felice, Ripa and Giampietro, 2017).

## A.6 Data sources of data processing in relation to Gross Value Added

### A.6.1 The processing of data

### *OPW*

By definition, activities in the Outside Paid Work compartment are not associated with the production of value added.

### *PW/SG/Transport/Public Transport and PW/SG/Transport/Transport of Goods*

In the case of transport activities in SG, data on VA was not available at that level of analysis. So we included this data only at the n-2 level in the global SG as explained in (V), with the corrected category: *52-53: Emmagatzematge i activitats afins al transport; activitats postals*.

### *(V) PW/SG/(Education, Healthcare, Offices, Commerce, Hotels, Bars and Restaurants, Other), PW/Manufacturing and Construction and PW/Energy Sector*

As discussed before, the activities of the shadow economy are not fully reflected in government statistics whereas the energy consumption of these activities are accounted in the energy balances of the city. So, it is important to try to estimate the missing VA and we used a criterion similar to the one used to estimate the missing data on working hours (H). A 22,3% of the GDP in the Barcelona province was produced by the black economy in 2009 (Gestha and Universitat Rovira i Virgili, 2014), and so we added an extra 22,3% of the VA in the statistics of the city ($\mathrm{VA}_{\mathrm{PW}_{\text{to allocate}}}$) across the sub-sectors.

The profile of VA across sectors comes from the statistics per economic sub-sectors - available online in the city council statistical website: *Gross added value in Barcelona for 39 industries. sectoral structure (%) and specialization index in relation to Catalonia. current prices* (Ajuntament de Barcelona, 2012a), the shares of the sub-sectors inside the larger sectors of 2014 were maintained and the values of VA for the larger sectors were taken from 2012 data in order to estimate the VA of the sub-sectors for 2012: *Gross value added at basic prices by sector in Barcelona and other areas. 2011-2012* (Ajuntament de Barcelona, 2012a). Finally, the criterion for the allocation of the extra quantity of shadow VA across the sub-sectors is made with the data of % of the black GDP for each sub-sector j at an European level ($\mathrm{p}_{\mathrm{blackGDP}_{\mathrm{j}}}$), in the report *The shadow economy in Europe 2013* (Schneider, 2013). Also, in this case we had to make assumptions about how to estimate values and to decide the profiles of allocation. This fact is not a problem in this exercise having the goal to illustrate the methodology. However, in a real study used to provide information to be used for decision making, it an open discussion with the users of the study should be made about these assumptions.

$$\mathrm{VA}_{\mathrm{PW}_{\text{to allocate}}} \cdot \mathrm{p}_{\mathrm{blackGDP}_{\mathrm{j}}} = \mathrm{VA}_{\mathrm{PW}_{\text{black j}}}$$

Finally, $\mathrm{VA}_{\mathrm{PW}_{\mathrm{j}}}$ is the sum of the calculated from statistics and the one from the shadow economy:

$$\mathrm{VA}_{\mathrm{PW}_{\mathrm{j}}} = \mathrm{VA}_{\mathrm{PW}_{\text{statistics j}}} + \mathrm{VA}_{\mathrm{PW}_{\text{black j}}}$$

### *(W) PW/Port*

The value added generated by the port has been taken by the documents of the Agència Portuaria (Port de Barcelona, 2017). In order to avoid double counting, this value of VA was subtracted from the category “others” in SG (which includes the sub-category *52-53: Emmagatzematge i activitats afins al transport; activitats postals* in the classification CCAE).

*Table A-7 Activities in the time use survey and proportion of the activity included in each element of the system, used in the end use matrix*

| | | | **MuSIASEM classification** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Households | Commerce | Bars and restaurants | Other (sports, arts, culture) | Education | Offices | Healthcare | Mobility | Other outdoor activites | Paid Work | Out |
| **Activities in time use survey** | Personal care | Sleep (Sleep, sick in bed) | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Eating | **0.75** | 0.00 | **0.25** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Other personal care (washing and dressing, other or unspecified personal care) | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Employment | Main job and second job (working time in main and second job - including coffee breaks and travel at work) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | **1.00** | 0.00 |
| | | Activities related to employment (lunch break, other or unspecified activities related to employment) | **0.75** | 0.00 | **0.25** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Study | School or university (classes and lectures, homework) | **0.15** | 0.00 | 0.00 | **0.05** | **0.80** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Free time study | **0.50** | 0.00 | 0.00 | 0.00 | **0.50** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Household and family care | Unspecified household and family care | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Food management (food preparation, baking and preserving, dish washing) | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Household upkeep (cleaning dwelling, cleaning garden, heating and water, arranging household goods and materials, other or unspecified household upkeep) | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Making and care for textiles (laundry, ironing, handicraft and producing textiles, other or unspecified making of and care for textiles) | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Gardening and pet care (gardening, tending domestic animals, caring for pets, walking the dog, other or unspecified gardening and pet care) | **0.50** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.50 | 0.00 | 0.00 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Construction and repairs (house construction and renovation, repairs to dwelling, making, repairing and maintaining equipment, vehicle maintenance, other or unspecified construction and repairs) | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Shopping and services (shopping, commercial and administrative services, personal services, other or unspecified shopping and services) | 0.00 | **0.90** | 0.00 | 0.00 | 0.00 | **0.05** | **0.05** | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Household management | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Childcare (physical care and supervision, teaching the child, reading, playing and talking with child, accompanying child, other or unspecified childcare) | **0.80** | 0.00 | 0.00 | 0.00 | 0.00 | **0.05** | 0.00 | 0.00 | **0.15** | 0.00 | 0.00 |
| | | Help to an adult family member (physical care of a dependent adult household member, other help of a dependent adult household member, help to a non dependent adult household member) | **0.95** | 0.00 | 0.00 | 0.00 | 0.00 | **0.05** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Voluntary work and meetings | Organisational work (work for or through an organisation) | 0.00 | 0.00 | 0.00 | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Informal help to other households (construction and repairs as help, help in employment and farming, care of own children living in another household, other childcare as help to another household, help to an adult of another household, other or unspecified informal help to another household) | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Participatory activities (meetings, religious activities, other or unspecified participatory activities) | 0.00 | 0.00 | 0.00 | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Social life and entertainment | Social life (socialising with family, visiting and receiving visitors, celebrations, telephone conversation, other or unspecified social life) | **0.50** | 0.00 | **0.50** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Entertainment and culture (cinema, theatre and concerts, art exhibitions and museums, library, sports events, other or unspecified entertainment and culture) | 0.00 | 0.00 | 0.00 | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Resting - time out | **0.75** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | **0.25** | 0.00 | 0.00 |
| | Sports and outdoor activities | Physical exercise (walking and hiking, jogging and running, cycling, skiing and skating, ball games, gymnastics and fitness, water sports, other or unspecified sports or outdoor activities) | 0.00 | 0.00 | 0.00 | **0.50** | 0.00 | 0.00 | 0.00 | 0.00 | **0.50** | 0.00 | 0.00 |
| | | Productive exercise (e.g. hunting, fishing, picking berries, mushrooms or herbs) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | **1.00** |
| | Hobbies and computing | Arts and hobbies (arts-visual,performing, literary-, collecting, correspondence, other or unspecified hobbies) | **0.80** | 0.00 | 0.00 | **0.20** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Computing (computing-programming, information by computing, communication by computing, other or unspecified computing) | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Games (Solo games and play, gambling, parlour games and play, computer games, other or unspecified games) | **0.75** | 0.00 | 0.00 | **0.10** | 0.00 | 0.00 | 0.00 | 0.00 | **0.15** | 0.00 | 0.00 |
| | Mass media | Reading (reading periodicals, reading books, other or unspecified reading) | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | TV, video and DVD | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Radio and recordings | **1.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Travel and unspecified time use | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | **1.00** | 0.00 | 0.00 | 0.00 |

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