Progress Report

Integrated analysis of the water-energy-food nexus of Andorra under the MuSIASEM approach for the transition to a more sustainable model

Anàlisi integrada del nexe aigua-energia-alimentació del Principat d'Andorra utilitzant la metodologia MuSIASEM per a la transició cap a un model més sostenible.

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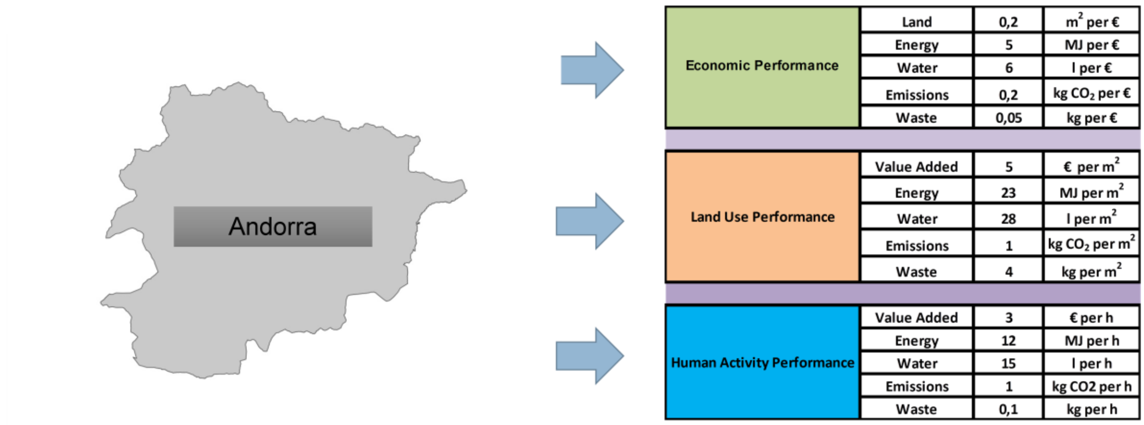

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Abstract

The Principality of Andorra has been identified by the scientific community as an area extremely vulnerable to climate change. In addition, the country has undergone a dramatic transformation from a mountain subsistence economy to an urban service economy specialized in tourism activities. Under this contextual framework, the main research question we are trying to answer is: what are the main biophysical requirements determining the sustainability of Andorra? This biophysical diagnosis is also relevant to assess the strategies that Andorra can follow to open up a possible pathway to a more sustainable development.

To this end, Andorra is understood as a thermodynamically open system and its societal metabolism is studied. The Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach is used to characterize the existing metabolic pattern of Andorra in relation to the water-energy-food nexus. At this stage of the research an End-Use Matrix and an Environmental Pressure Matrix have been constructed. In addition the results obtained have been compared with other geographical areas.

In short, the ultimate goal of the research is to generate quantitative information, based on a robust analytical framework, to have a better informed discussion about the option space of a transition to a more sustainable development in Andorra.

Resum

El Principat d'Andorra ha estat identificat per la comunitat científica com una zona extremadament vulnerable al canvi climàtic. A més, el país ha experimentat una dramàtica transformació des d'una economia de subsistència a una economia de serveis especialitzada en activitats turístiques. En aquest marc contextual, la principal pregunta de recerca que intentem respondre és: quins són els requeriments biofísics que determinen la sostenibilitat d'Andorra? Aquest diagnòstic biofísic és també rellevant a l'hora d'avaluar les estratègies que Andorra pot seguir cap a un desenvolupament més sostenible.

Entendrem Andorra com un sistema termodinàmic obert i estudiarem el seu metabolisme social. Per a això, utilitzem la metodologia Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), amb la finalitat de comprendre el patró metabòlic d'Andorra en relació al nexe aigua-energia-alimentació. En aquesta fase de la recerca, una Matriu d'Usos Finals i una Matriu de Pressions Ambientals han estat construïdes. A més els resultats obtinguts han estat comparats amb els d'altres àrees geogràfiques.

En conclusió, l'objectiu últim de la recerca és generar informació quantitativa útil, basada en un marc analític sòlid, per a tenir un debat millor informat sobre l'espai d'opcions per a la transició cap a un desenvolupament més sostenible a Andorra.

Acronyms

AG: Agriculture

E: Electricity

ELP: Economic Labor Productivity

ELUP: Economic Land Use Productivity

EMD: Exosomatic Metabolic Density

EMR: Exosomatic Metabolic Rate

EPM_{EXT}: External Environmental Pressure Matrix

EPM_{INT}: Internal Environmental Pressure Matrix

ET: Energy Throughput

EUM_{EXT}: External End-Use Matrix

EUM_{INT}: Internal End-Use Matrix

F: Fuel

GER: Gross Energy Requirement

GDP: Gross Domestic Product

GHG: Greenhouse Effect Gases

GVA: Gross Value Added

H: Heat

HA: Human Activity

HH: Household

ICM: Industry, Construction and Manufacturing

Litecc: Law on the impetus of energy transition and climate change

LU: Land Use

MEFA: Material and Energy Flow Analysis

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

NML: Non-Managed Land

OE: Orthodox Economics

PW: Paid Work

SES: Social-Ecological System(s).

SG: Service and Government

SMR: Sociometabolic Research

WEF Nexus: Water-Energy-Food Nexus

WMD: Water Metabolic Density

WMR: Water Metabolic Rate

WT: Water Throughput

Units of energy:

Kilo (k): 10^3 Mega (M): 10^6 Giga (G): 10^9 Tera (T): 10^{12} Peta (P): 10^{15}

1. Introduction.

In the XXI century, the most complex challenges facing humanity, including climate change, transition to a renewable energy base, limits to growth, plastic pollution, urbanization, peak oil (and peak everything) and biodiversity loss among others, reveal the existence of external biophysical limits (Melgar-Melgar and Hall, 2020). The surging human use of biophysical resources (materials and energy), which results from the pursuit of social and economical goals, generates an unquestionable environmental deterioration as a result of the excessive pressures of human systems on the natural world (IPBES, 2019; UN Enviromemnt, 2019). Consequently, the planetary equilibrium that allows the sustainability of human societies is in danger (Steffen et al., 2018) and time to avoid irreversible changes is running out (Masson-Delmotte et al., 2018).

The Principality of Andorra, a small mountainous country located in the Pyrenees (figure 1), is not divorced from this reality.

Figure 1. Geographical location of Andorra. Source: Google Maps.

On one side, the country has undergone during the twentieth century a dramatic transformation from a rural economy of subsistence to an urban economy specialized in the service sector, mainly in tourism and financial activities, embedded in global flows of capital and people (Lluelles and García, 2018). As a mountain area is vulnerable to climate change (IPCC, 2007) but at the same time contribute to the generation of local and global environmental pressures with the intensification of tourist activities. The improvement of mobility and communication technologies in the last decades has increased the number of permanent and temporary residents, tourists and seasonal workers resulting in an overall increase in the consumption of food, energy, water and other material flows. Andorra is a site of high population density and therefore of intense metabolic transformations.

On the other side, Andorra as a member of The United Nations (UN) acceded to the United Nations Framework Convention on Climate Change, as non-Annex I Party on the 2nd March 2011, and is therefore subject to the Parties specific obligations (Miquel et al., 2021). Additionally, the Andorran Government presented the project "Projecte de llei de la transició energètica i el canvi climàtic" (2018) which was passed by the Consell General as "Llei 21/2018 del 13 de setembre, d'impuls de la transició energètica i del canvi climatic" (Litecc)[1]. This law lays the foundations for a more sustainable development under the normative narrative of achieving greater energy sovereignty and moving towards a carbon-neutral society. The main objectives it raises are:

- Reduce energy intensity (measured in TOE/M€[2] of GDP) by at least 20% in 2030 and 30% in 2050 compared to base year 2010.
- Reduce annual greenhouse gas emissions in relation to a "business as usual" scenario by at least 37% in 2030.
- Increase national electricity production to at least 33% of the demand by 2030 and 50% by 2050.
- Ensure a percentage of energy from renewable sources in relation to national electricity production not less than 75%.
- Increase the percentage of electric vehicles in the national vehicle fleet to 20% by 2030 and to 50% by 2050.
- Halving emissions from the domestic transport sector.

However, when discussing sustainable development there are no optimal or win-win solutions (Velasco-Fernández, 2020). Plans for a rapid decarbonisation of the economy are in general reflecting superficial visions —based on the adoption of a single scale (the country as a whole) and a single dimension (*exosomatic energy*[3]) of analysis— where the following relevant aspects of the sustainability discussion are systematically ignored:

- The existence of limits of a different nature. Decarbonization of the economy is closely linked to other environmental challenges, such as water scarcity, displacement of land or biodiversity loss. This requires the integration of information from different dimensions (economic, biophysical, demographic and ecological), considering different levels of analysis (the whole, compartments and sub-compartments) and different spatial and temporal scales (Giampietro and Mayumi, 2000; Nilsson et al., 2016).

[1] Available at this link
[2] TOE/M€: Tonne of oil equivalent/million euro.
[3] Relevant concepts in *italics* are explained in detail in the glossary (Appendix 1).

- The existence of tensions between different concerns, e.g. aspiration for economic growth and the need to preserve the environment (Naredo, 2019).
- The dominance of orthodox economics (OE)'s narratives where discussions appears to be based on the endorsement of policy legends (Giampietro and Funtowicz, 2020) about perpetual economic growth (and decoupling of economic growth from natural resource consumption), efficiency, use of market instruments and the promise of technological silver bullets more than in sound quantitative analysis (Parrique et al., 2019).

As a result, robust knowledge claims —based on a strong biophysical foundation and a system thinking approach— are removed from the discussion in relation to Andorra's plans for sustainability. With the aim of counteract these shortcomings, this thesis proposes a biophysical approach, developed within the theoretical framework of the sociometabolic research, in order to have a better informed discussion about the transition to a more sustainable model in Andorra.

A biophysical approach characterizes how societies use natural and human-created resources and how social-economic systems simultaneously depend on and place pressures on processes taking place in ecosystems. In this way it becomes possible to adopt an effective framing of sustainability issues to address questions such as: Why different resources are used in the economy? What type of primary sources (e.g. fossil fuels, uranium and land) and secondary inputs (e.g. energy carriers, blue water, and processed material) are employed to express the various functions of the economy? By whom? To what extent are environmental costs shifted to other *social-ecological systems* (SES) because of imports? The approach shows what is possible and what is not in accordance with the existing technological context and the availability of natural and social resources acknowledging the existence of biophysical limits (González de Molina et al., 2019). Under this framework traditional economic analysis (focusing on monetary valuations) is not replaced, rather a biophysical approach provides an alternative framing of analysis capable of integrating the consideration of different aspects relevant for the discussion over sustainability.

In order to facilitate the proposed approach, we understand Andorra as a dissipative structure (Prigogine and Nicolis, 1977) and want to study its metabolism, focusing on the water-energy-food nexus (WEF nexus). The concept of WEF nexus has emerged over the past 15 years as a powerful framework for understanding the relationships, and critiquing established distinctions, between categories of environmental governance that have traditionally been managed in separation (D'Odorico et al., 2018; Williams et al., 2019). The characterization of the WEF nexus will be carried out following the *Multi-scale Integrated Analysis of Societal and Ecosystem*

Metabolism (MuSIASEM) approach developed by Giampietro et al. at the Institute of Environmental Science and Technology (ICTA). The MuSIASEM approach has been consolidated as a theoretical and methodological framework capable of integrating information about environmental, social and economic aspects. In MuSIASEM, the external referent for the entanglement between the observed flows of water, energy and food is the *metabolic pattern* of SES (Giampietro, 2018). In turn, the metabolic pattern comprehends the various processes of conversion of energy and materials inputs needed to reproduce the structural elements and express the expected functions of the system under analysis, maintaining its identity. Thus, the characterization of the metabolic pattern of Andorra is the cornerstone of this research work.

At the current Andorra's juncture, the contribution of the thesis under development is particularly relevant. Before embarking in plans for sustainability a baseline of biophysical indicators is needed (Melgar-Melgar and Hall, 2020). In this sense the analysis of the metabolic pattern of Andorra should provide with:

1. An increasing understanding of the nexus over the biophysical flows required for sustaining and reproducing the Andorran social-economic system. This diagnostic phase should allow the characterization of Andorra's deep dependencies on other SES. It also should properly consider the emergent competition for different natural resources (e.g. water, land and materials) between different functional compartments of the Andorran society (e.g the energy sector, the agricultural sector or the tourist sector), that the transition to a low-carbon society will probably aggravate. Finally, this biophysical diagnostic should lead to a better perception of the strong interrelation and tensions between social and economic goals and environmental ones.

2. A better control of the quality of the narratives used in the policy discourse in Andorra. In this sense the research work should help to have a more informed discussion about the plausibility of achieving greater energy sovereignty if we have in consideration *endosomatic energy* (food) and exosomatic energy (energy). It also should improve the quality of the debate on the convenience of using simple input/output indicators (e.g. energy intensity) to capture complex processes by adding qualitative and contextual information across multiple scales and dimensions, i.e. generating a multi-level and multi-dimensional information space.

In short, the sustainability predicament of Andorra, in a context of globalization, uneven geographic development, climate change and resource depletion, requires an approach capable of generating a holistic analysis. The complexity of the information related to sustainability issues need to integrate information that is often partial or too specific and then critically frame sustainability debates to improve deliberations. The thesis under development uses a robust analytical framework —the MuSIASEM approach— to share relevant information about the concerns and problems to be solved. However, an integrated analysis of the metabolic pattern recognizes the impossibility to achieve a unique or optimal solution. Instead it provides valuable insights on "where we are" (diagnosis), how to get a robust analysis of the option space for sustainable solutions and how to implement them (it allows to check the quality of the narratives used to discuss solutions).

This document is structured as follows: next section synthesizes the main characteristics of sociometabolic research. Section 3 addresses the MuSIASEM approach, a methodological approach within sociometabolic studies with important theoretical and practical peculiarities. Section 4 states research objectives. Section 5 describes how the selected methodology is applied to study the Andorran social-ecological system in order to tackle the research objectives. Here, the main sources of data collection and limitations are considered. Section 6 presents some provisional results. Section 7 lists some preliminary insights. Section 8 illustrates the work plan until the completion of the doctoral thesis. The interested reader can consult the annexes for a definition of theoretical terms, the articles submitted for publication and a provisional index of the doctoral thesis.

2. Sociometabolic research.

The MuSIASEM approach has been consolidated as a theoretical and methodological framework capable of integrating information from different dimensions (e.g. economic, social, biophysical) and scales of analysis. However, it belongs to a broader framework known as sociometabolic research. Sociometabolic research includes a wide range of approaches for measuring, analyzing and modeling the study of flows of energy and materials between society and nature. This section summarizes sociometabolic research's main characteristics and traditions.

2.1. Main principles.

The concept of "social metabolism" (or "economic", "socio-economic" or "societal" metabolism), from this point defined as "sociometabolic research" (SMR) grew from the observation that biological systems (e.g. organisms, ecosystems) and socioeconomic systems (e.g. households, firms, economies) decisively depend on a continuous throughput of energy and materials in order to maintain their internal structure. More specifically, "social metabolism" refers to all energy and material transformations that are taking place *within* an open social system, such as an economy, and *between* this system and its environment. These complex processes determine the functional and structural elements of the system, ensure its reproduction, maintain and repair its parts, and present specific dynamics according to different contexts (Giampietro et al., 2012).

SMR has become an effective way to indicate the existence of a clear knowledge gap in the mode the economic process is represented. In this sense, if we evaluate the performance of the economy only by its growth rate measured in monetary terms, it is not possible to visualize the pressure of the economic process on the environment (and on people) in the resulting representation. At the present, SMR has become a leading paradigm for the analysis of society-nature interactions (Fischer-Kowalski and Haberl, 2015; Fischer-Kowalski and Weisz, 2016; Gerber and Scheidel, 2018).

SMR is based on the assumption that social systems and ecosystems are complex systems that reproduce themselves, interact with each other and co-evolve over time (Fischer-Kowalski and Weisz, 1999; González de Molina and Toledo, 2014). This acknowledgement helps to better deal with the sustainability predicament, where challenges from different dimensions are strongly interlinked, by providing quantitative, comprehensive research capable of linking social, economic and environmental domains to guide and monitor progress towards sustainability. SMR allows to study the implications of the "size" or "scale" of human activities compared with the biosphere (Daly, 2005) and, therefore, is one of the main topics of that transdisciplinary field that is ecological economics (Martinez-Alier and Muradian, 2015; Naredo, 2015; Røpke, 2004).

Explicitly or implicitly, SMR builds on the following assumptions (Haberl et al., 2019): (i) The functioning of social systems, including the economy, rests on successfully organizing energy and material flows to expand, maintain and operate its biophysical basis: human population, livestock and artefacts such as buildings, infrastructures or durable commodities. These fund elements generate important flows, such as physical, intellectual or emotional labour, products such as bread, clothes or electricity, and services such as living space or mobility. (ii) The composition, magnitude and patterns of social metabolism determine society’s environmental pressures and impacts. Sustainability requires sociometabolic flows to be compatible with the supply and sink capacity of the biosphere. And (iii) important principles of the natural sciences (for example, the laws of thermodynamics) apply to the metabolism of socioeconomic systems and are fundamental to their understanding.

The interested reader can consult Martinez-Alier (1987) and Fischer-Kowalski (1998) for the long history of attempts to integrate economic analysis with biophysical analysis with the aim to improve our understanding of the functioning and evolution of human society. Also the works of González de Molina and and Toledo (2014) and Tello (2013) for a synthesis of the different topics related to the concept of social metabolism.

And updated discussion of the contributions of SMR and future research directions can be found in a recent paper in Nature Sustainability (Haberl et al., 2019).

2.2. SMR traditions.

Social metabolism (and SMR) is a concept that gained extraordinary strength in the field of socioenvironmental studies since the 1990's. Throughout this decade, methodologies for it have been formalized and have been applied in tens of case of studies. As a consequence, we currently have detailed evidence available allowing for better understanding the biophysical dynamics of societies, especially industrialized societies (González de Molina et al., 2019; Haberl et al., 2019).

According to Gerber and Scheidel (2018) we can consider six main methodological approaches within sociometabolic studies: (i) MuSIASEM (Giampietro et al., 2012, 2013, 2014); (ii) Material and Energy Flow Analysis (MEFA) (Fischer-Kowalski and Haberl, 2007; Haberl et al., 2016); (iii) material and substance flow analyses (Ayres and Kneese, 1969; Baccini and Brunner, 2012); (iv) input-output analyses (Leontief, 1986); (v) life-cycle analyses (European Union Joint Research Center, 2010); and (vi) energetics analyses (Smil, 2015, 2008). Other specialized instruments in the sociometabolic toolkit include the Energy Returned on Energy Invested (EROI), virtual water, ecological footprint, ecological rucksacks, and various "hybrid" approaches (Pauliuk et al., 2015). Some overlaps may thus exist between these methods and the differences mainly lie in their purpose, scope and data requirements. However, there is still an open debate on whether all the methodological approaches included under this heading address the basic mechanism associated with the meaning of the term metabolism (Giampietro et al., 2012). As a result, more of these works are lacking theoretical and methodological reflections (González de Molina and Toledo, 2014).

3. Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM).

3.1. General ideas.

Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is an innovative method to better characterize how societies use natural and human-created resources and how social-economic systems simultaneously depend on and place pressures on processes taking place in ecosystems. MuSIASEM is one of the main methodological approaches found in sociometabolic studies (González de Molina and Toledo, 2014; Haberl et al., 2019). According to Gerber and Scheidel (2018), MEFA and MuSIASEM are today the two major SMR approaches for the substantive ("in kind") study of the economy as a whole, not only focusing on a particular resource use. Yet, the originality of MuSIASEM lies in having a robust theoretical basis as a consequence of a sophisticated combination of concepts belonging to complex systems science (Giampietro et al., 2012, 2013, 2014; Giampietro, 2019; Giampietro and Renner, 2020; Renner et al., 2020b) which can deal with the epistemological challenge associated with the consideration of different aspects relevant for the discussion over sustainability. In particular the adoption of the *flow-fund model* of Georgescu-Roegen (1971) allows the MuSIASEM accounting framework to compare the size of the fund elements used by the economic process in its different functional compartments with the size of the ecological fund elements affected by the expression of the societal metabolism. For a detailed discussion about the characteristics of the methodology, its theoretical foundations and its inclusion in the general framework of ecological economics, the interested reader can consult the attached articles (Appendix 2).

MuSIASEM accounting has been used for integrated assessments of agricultural systems (Cattaneo et al., 2018; Giampietro, 2003; Scheidel and Farrel, 2015), biofuels (Giampietro and Mayumi, 2009), nuclear power (Diaz-Maurin and Giampietro, 2013; Diaz-Maurin and Kovacic, 2015), energetics (Giampietro et al., 2013; González-López and Giampietro, 2018), sustainability of water use (Madrid-Lopez and Giampietro, 2015), mining (Silva-Macher, 2016) and urban waste management (Chifari et al., 2018; D'Alisa et al., 2012). Moreover the methodology has been applied to assess societal metabolism at the municipal (Pérez-Sánchez et al., 2019), regional (D'Alisa and Cattaneo, 2013), national (Giampietro et al., 2012; Velasco-Fernández et al., 2015) and European level (Velasco-Fernández, 2017; Velasco-Fernández et al., 2018). An application of MuSIASEM to the nexus between natural resources is in the book "Resource Accounting for Sustainability: The Nexus between Energy, Food, Water and Land Use" (Giampietro et al., 2014). This work has been tested in collaboration with Food and Agriculture Organization (FAO, 2013). Besides, the use of MuSIASEM for the analysis of the nexus biophysical flows has been further developed under the European project "Moving Towards Adaptive Governance in Complexity: Informing Nexus Security" (MAGIC), a four-year project funded under the H2020-WATER-two-stage programme (Cabello et al., 2019; Cadillo-Benalcazar et al., 2020, 2021; Di Felice et al., 2019; Giampietro et al., 2020; Giampietro and Funtowicz, 2020; MAGIC Consortium, 2020; Pérez-Sánchez et al., 2020; Renner et al., 2020a; Velasco-Fernández et al., 2020a).

The main difference between MuSIASEM and other analytical tools belonging to the family of conventional input/output analysis (Leontief, 1986) is simple. Conventional input/output assessments are based on the analysis of how inputs and outputs change in time (for example, from year to year), without inferring how the relations over inputs and outputs co-evolve and co-determine on each other. This is also the epistemological stand of some metabolic studies as life cycle analysis and MEFA and in general the family of footprints tools (Giljum et al., 2013; Hoekstra and Wiedmann, 2014). The robustness of these studies is based on the utilization of large databases used to assess output/input relations assumed to be useful to produce a meaningful characterization of the observed systems. On the contrary, MuSIASEM examines the characteristics of metabolic elements in terms of "expected" metabolic patterns, whose robustness is given by the entanglement of metabolic relations over functional and structural elements. The quantitative characterization is the result of a combination of data collected at different levels and across different dimensions of analysis. So, when analyzing for instance a metabolized flow of food, i.e. a given amount of kcal of food/year, we have to specify both extensive (quantities) and intensive (qualitative metabolic characteristics) of the elements of the system: i.e. a societal fund that is consuming it (e.g. number of days of people x kcal/day p.c.); (ii) a ecological fund that is producing it (e.g. number of hectares x yield of food per hectare), and (iii) their expected relation in the metabolic pattern. In this way we can explore the forced relations of congruence between the relative size of the funds (pace and density of production and consumption) and identify the role played by the imports in balancing the requirement and supply of flows. This type of relational analysis is not based on deterministic predictions (of the "ceteris paribus" type used in OE) but on contingent definitions of the option space. These impredicative relations can be checked using different metrics (energy, water, food, money).

3.2. Understanding and characterization of sustainability.

MuSIASEM opens the way for a quantitative and qualitative contextualization of the sustainability of social-economic systems based on the study of the metabolic pattern. The metabolic pattern refers to the various processes of conversion of energy and materials inputs, used to reproduce structural elements and express the expected functions. This can be expressed as metabolic rates, in terms of resource use per hour of human activity, or metabolic densities in terms of resource requirements for different land uses (e.g. agricultural, industrial, residential, etc.). Thanks to the expression of a certain metabolic pattern it is possible to stabilize the metabolic network (i.e. the expected set of relations over constituent components of the social-economic system) and, therefore, its identity.

An analysis of sustainability, in order to be useful to inform policy, should provide a diversified quantitative representation of key characteristics of the system we want to control (e.g. the different factors determining the stability of the metabolic pattern of the studied system). MuSIASEM distinguishes among four types of sustainability concerns (Giampietro et al., 2020):

1. *Feasibility (external view)*: The analytical framework must be able to check the compatibility of the metabolic pattern of society with the existence and severity of external biophysical constraints. This involves constraints that result from the interaction of the social-economic system with ecological systems, i.e. the biosphere, both on the supply and sink side. On the supply side we can think about the limits on the availability of land, water, fertile soil, solar radiation, primary energy sources or minerals. On the other hand, on the sink side we can include limits to the GHG emissions, solid waste disposal and leakage in water bodies among others. In MuSIASEM these constraints are considered beyond human control. The feasibility concern requires considering the metabolic pattern associated with the social-economic activity as a black box interacting with its context. It also means characterizing the "size" of the metabolism of the social-economic system in relation to the size of the processes providing supply and sink capacity for the primary flows exchanged. This involves the identification and quantification of the different types of environmental pressures that the social metabolism is exerting on its context.

2. *Viability (internal view)*: The analytical framework must also be able to check the severity of internal biophysical and economic constraints operating inside the social-economic system (the local technosphere). These constraints are determined by processes under human control and include: (i) technological capability; (ii) economic viability; and (iii) labour supply/shortage (associated with socio-demographic variables). This concern requires looking at what is going on inside the black box in order to characterize the state of the system.

3. *Openness*: The analytic framework must be able to check the degree of openness of the system, that is, the degree of domestic control over and responsibility for the production processes supplying the inputs metabolized by the system. These inputs may refer to both primary flows (supply and sink capacity made available by natural processes outside of human control) and secondary flows (made available by technical processes under human control). Hence, the openness of the system refers to the degree of dependence of a society on other SES. This in particular important in today's globalized world where only part of the production processes needed to supply the internal consumption takes place within the borders of the social-economic system considered.

4. *Desirability (normative view)*: Desirability refers to the perceived acceptability of the living conditions associated with the expression of the metabolic pattern: social practices associated with affective relations are entangled with end uses associated with technical relations. This implies that in order to assess desirability it is necessary to extend the analysis beyond biophysical variables and economic narratives, by considering also matters of values, desires, belief as well as cultural, social and political arrangements. Addressing the desirability of the metabolic pattern of a social-economic system requires a reflection on the identity of the society

which is preserved. A reflection that call for a *post-normal science* rationale (Funtowicz and Ravetz, 1993).

In conclusion, the analysis of the state of the system (viability or internal vision), allows only the observation of the metabolism of secondary flows (e.g the energy carriers, food products and other goods consumed in the economic process). To explore the interaction of the system with its local environment (feasibility or external vision) we have to couple the state of the system (what is going on inside the technosphere) with the set of environmental pressures resulting from the interaction of the system with the environment (what is going on inside the biosphere). This needs the adoption of a different descriptive domain and metrics. The study of the state-pressure relation, defined at the large scale, requires an accounting system than can track primary flows: flows crossing the interface between the technosphere and the biosphere either extracted from primary sources or dumped into primary sinks. Therefore, the MuSIASEM approach makes it possible the combination of different levels of observation —using non-equivalent accounting categories— for an integrated analysis of the sustainability problem.

3.3. Stages of implementation.

The application of the MuSIASEM accounting framework responds to different stages (see table 1). The following subsections summarize the MuSIASEM-based accounting protocol in its standardized version (Giampietro et al., 2014).

3.3.1 Pre-analytical definitions.

- Step 1: Definition of the social-economic system as a set of hierarchically organized functional compartments (made up by structural elements) embedded in a natural system.

A system is a set of elements that expresses meaningful interactions. In the case of sustainability analysis, the system is a social-ecological one. This expresses a metabolic pattern desirable for the people living in, that when needed can be adapted to new boundary conditions (changes on the outside) or new aspirations (changes on the inside). Therefore, a social-ecological system is a set of constituent components (a set of parts represented by a combination of structural and functional elements) that because of their coordinated interaction preserve and adapt the identity of the whole in time. This entails preserving the identity of: (i) its *structural elements*; (ii) its *functional elements*; and (iii) the establishment and maintenance of a set of relations over the characteristics of the structural and functional elements expressing the emergent property of its identity (Giampietro and Renner, 2020). Therefore, we have to define first the overall system at the level n (the identity of the system, a pre-analytical choice establishing the boundaries of the system). Then, within this functional whole, we can identify a set of lower-level functional compartments at level (n-1) (e.g. household sector, paid work sector) on the basis of the functions expressed in society (e.g. reproducing human labor, generation of income). These lower-level compartments can be further subdivided (levels n-2, n-3, etc.) into other functional/structural elements. The generation of a hierarchy of sub-compartments not only allows to single out certain aspects of societal functioning but also permits to confront large-scale assessments (i.e. top-down assessments based on aggregate statistics) with local-scale assessments (i.e. bottom-up assessments based on technical coefficients observed at the local scale).

Table 1. Stages of MuSIASEM

Stages of MuSIASEM
1.DEFINITION
1.1. Identification of the constituent components associated with the metabolism of the system
1.2. Definition of fund elements to characterize constituent components (extensive)
1.3. Definition of flow elements metabolized by the constituent components (extensive)
1.4. Definition of the metabolic characteristics (flow/fund ratios — intensive)
1.5. Data gathering (top-down/bottom-up approach) — across different domains
2.DIAGNOSIS
-End-Use Matrix (EUM)
-Environmental Pressure Matrix (EPM)
-Externalization Matrix (EM)
3. ANTICIPATION
-Explore the feasibility, viability and desirability of alternative "state-pressure-externalization" combinations to test the sustainability of different scenarios with the available information
-Explore the possibility of changing the relations between state and environmental pressures associated with changes in both social practices or technology

- Step 2: Definition of fund elements over the functional compartments of the system.

This step involves the selection of relevant fund elements and their allocation to the various functional compartments of the system. Usually, *Human Activity* (HA) and *Land Use* (LU) are considered as the fund elements to characterize the constituent components of the system studied. Human activity (measured in hours) is the key fund element for socio-economic analysis, on which the definition and size of functional compartments are based. The fact of using hours of human activity allows recognizing the diversity of activities carried out within a socioeconomic system and distinguishing the activities of the paid-work sector (where typologies of human activity are described as economic jobs) with other activities done at home or outside work (where typologies of human activities are described as specific forms of social practices). Land use (measured in hectares) is also a key dimension of the analysis, land representing the fund that refers to the environment and ecosystem uses in the study area. Thus, the selected fund variables must be quantified and distributed over the compartments defined at step 1 respecting the congruence constraint of "closure" over the different hierarchical levels of analysis, i.e. the sum of the size of the fund elements described at given level n must be equal to the sum of the size of the fund elements described at the level n-1.

- Step 3: Definition of the various flows (food, energy, water, money) used by the selected fund elements.

MuSIASEM connects funds (the agents and transformers of a process) and flows (the elements that are utilized and dissipated) inside the metabolic pattern across different levels of analysis. MuSIASEM has developed specific *grammars* for food, energy, water (figure 2) and the accounting for human activity and socio-economic characteristics. These grammars can be considered as relational maps for the user of MuSIASEM that become accounting categories one applied to the system under study.

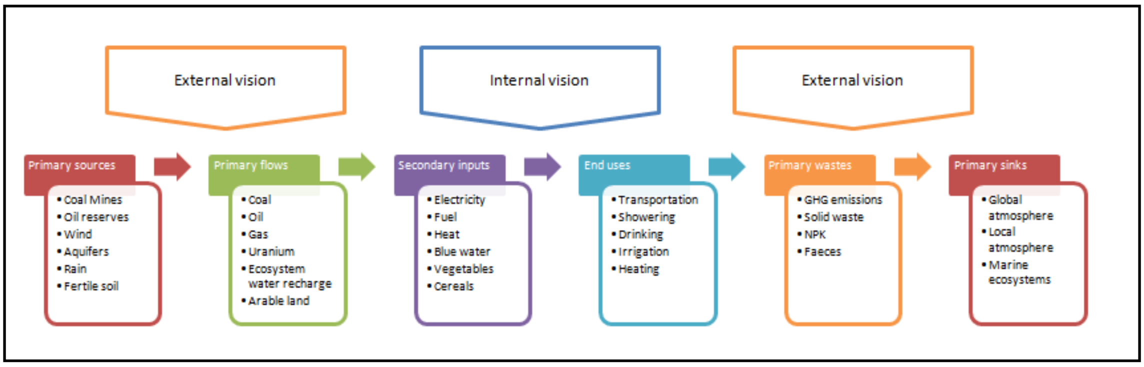


Figure 2. Categories of accounting on the two interfaces of the metabolic pattern of SES and some examples.

- Step 4: Definition of metabolic characteristics.

The methodology uses *intensive and extensive variables* which effectively describe (diagnostic mode) the requirements of the nexus biophysical flows guaranteeing survival and reproduction of the considered system. The specific flow/fund ratios calculated at different levels of analysis are the intensive variables, characterizing qualitative aspects of the fund elements per unit. Examples of flow/fund ratios are the *exosomatic metabolic rate* (EMR), measured in MJ/h, which allows characterizing the exosomatic energy consumption per hour of human activity in each functional compartment; the *water metabolic density* (WMD), measured in m^3/ha, characterizing the blue water consumed per hectare in each functional compartment; or the *economic labour productivity* (ELP) which reports on added value generated per hour worked (in €/h). On the other side, the size of societal compartments, providing information on the structural relation between the functional parts and the whole, as well as different types of resource requirements are based on extensive variables.

As noticed earlier, in this system of accounting the definition of constituent components is mutually exclusive. This means that extensive variables describing their size must maintain closure across different levels of analysis. This is what determines a forced set of metabolic relations over the size of the constituent components and their metabolic pace through different hierarchical levels. For example:

Total energy throughput (TET)= Total human activity (THA) x energy metabolic rate (EMR) (level n)=[HA_{HH} x EMR_{HH}] + [HA_{PW} x EMR_{PW}] (Level n-1). Therefore, the metabolic energy requirements of the society as a whole (level n) depends on four distinct factors that can only be observed at the level n-1: the human activity of the household sector and the paid work sector (HA_{HH} and HA_{PW}) and the pace of energy metabolism in the household sector and the paid work sector (EMR_{HH} and EMR_{PW}).

- Step 5: Data gathering.

MuSIASEM allows for the combination of top-down and bottom-up strategies to gather data. Top-down strategies use statistical data to characterize the metabolic characteristics of the components of the system, for instance, gross energy requirement for the maintenance of household activities divided by the hours of human activity devoted to residential activities provided a benchmark about the metabolic rate in the HH sector. Bottom-up strategies use benchmarks for specific types of structural elements that can be scaled-up to explain the metabolic characteristics of the components. For instance, if we know the characteristics of different typologies of households, their different energy metabolic requirements and their size we can estimate the total amount of energy used in the HH sector in a certain period, by scaling up the average benchmarks of an average household by multiplying by the number of households. This double check guarantees the robustness of the analysis of the metabolic pattern since the characteristics of the whole and the main compartments observed at the larger scale must be compatible with those of the sub-compartments and the lower-level elements observed at the local scale (Giampietro and Bukkens, 2015).

3.3.2. Diagnosis.

The resulting quantitative information can be organized in the following three matrices (the *MuSIASEM toolkit*), which, when integrated, generate a complete diagnosis of the metabolic pattern of the system under study, i.e. how the system uses energy, water and food to reproduce itself:

1. ***The end use matrix (EUM)*** to generate a quantitative characterization of the state of the system. It provides a characterization of the pattern where different quantities of human activity and land (funds) and different

categories of flows are invested across different functional and structural elements, something known as the *mosaic effect* in the jargon of MuSIASEM (Giampietro et al., 2012). With this we obtain a quantitative representation of how the different flows are metabolized inside the technosphere for the realization of the various functions required to maintain the system. The EUM allows tracking "who is using what type of flows, why, how and how much". The integrated analysis provided by the EUM of the metabolic rates and densities of flows in different compartments of the society provides a holistic picture of sustainability and contribute to decision-making by avoiding partial information.

2. ***The environmental pressure matrix (EPM)*** to generate a quantitative characterization of the state-pressure relation of the system in its interaction with its natural environment. Because social-economic systems are not in thermodynamic equilibrium, they are open dissipative systems whose identity depends on the expression of a metabolic pattern. Thus, the internal process of dissipation (the state) has to be compatible with the existence of favourable boundary conditions in their environment (admissible environmental pressures). To study the state-pressure relation associated with a realization of a SES we have to establish a link between the representation of the processes under human control inside the system (the secondary inputs produced and consumed on the socioeconomic side) and the representation of processes beyond human control going on outside the technosphere (on the ecological side). This entails characterizing in an integrated way the factors determining coherence in the interface between the metabolized flows inside the technosphere and the primary flows coming from and going to the biosphere. Thus, the EPM tracks the supply of primary flows (e.g. tons of oil or uranium, cubic meters of water for generation of hydroelectricity, hectares of fertile soil to produce food) and the generation of primary wastes (e.g. greenhouse gas emissions, generation of wastes, etc.) associated with the secondary inputs metabolized in the EUM. To achieve this result, it uses the information available to characterize the profile of inputs and outputs coming from and going to the biosphere used to the structural elements operating in the technosphere to perform the functional task assigned in the economy.

3. ***The externalization matrix*** to generate a quantitative assessment of how much the state-pressure relation is altered by trade. The option of importing allows a country to ease both internal requirement of economic production factors (by avoiding the labour and technology required for the production of the imported goods and overcoming potential viability constrains) and environmental pressures (by avoiding the local use of natural resources and sink capacity for the production of imported goods and overcoming potential feasibility constraints). The practice of externalizing the required production factors to other SES has become so common that there is not a direct relation between what is produced and what is consumed inside the borders of a country. The externalization

matrix requires differentiating between: the *External End-Use Matrix* (EUM_{EXT}) and the *Internal End-Use Matrix* (EUM_{INT}); and between the *External Environmental Pressure Matrix* (EPM_{EXT}) and the *Internal Environmental Pressure Matrix* (EPM_{INT}).

3.3.3. Anticipation.

The "*Sudoku effect*" (Giampietro et al., 2014) is employed in scenario analysis of the metabolic pattern (simulation tool) so as to simultaneously consider different types of constraints defined at different levels of analysis. Energy, human time, power capacity and other biophysical flows available to the whole represent a set of finite resources to be shared by the internal functional compartments. Their allocation among societal functions determine reciprocal constraints allowing for the expression of the metabolic pattern and creating the "Sudoku effect", since different compartments are competing for consuming the same resources at given rates. These impredicative constraints (what is expected by the whole and what can be supplied by the parts) must be considered when investigating new societal configurations. Possible changes to the existing metabolic pattern can be obtained either by introducing new policies and innovations (different values of flow/fund ratios when expressing the actual set of end uses) or promoting alternative social practices (reshuffling the definition of end uses and their relative importance).

The methodology uses the term "anticipation" instead of "future scenarios". This is so because rather than produce quantitative results determined by a given set of supposed uncontested pre-analytical assumptions, MuSIASEM runs by generating an option space accommodating several possible results. It also works "via negativa" eliminating scenarios that are not biophysically feasible. Finally, the methodology considers a framework of post-normal science which explicitly acknowledges the presence of scientific uncertainty and value pluralism in the sustainability discussion.

4. Research objectives.

The thesis is framed within the naturalistic paradigm. In this sense it aims to accumulate information from different dimensions (biophysical, economic, demographic) to describe (collect as much information as possible on the essence of reality) about what the Andorran SES is and does to reflect on the sustainability of Andorra from different considerations relevant to different actors, i.e. under a general framework of incommensurability of values (Martinez-Alier et al., 1998). As stated in section 1, we understand Andorra as a dissipative structure, i.e. an open metabolic system whose structures and functions (its state) are stabilized by a continuous flow of inputs taken from the environment (energy and matter) and a continuous flow of outputs released to the environment (wastes and emissions), which leads to a pressure on the environment. Thus, we want to study its societal metabolism.

The main research question we are trying to answer is: in a complex context (section 1) what are the main biophysical requirements determining the sustainability of Andorra? Therefore, the principal research objective is to describe the biophysical requirements of the WEF nexus using the MuSIASEM approach for an informed discussion on the sustainability predicament of Andorra.

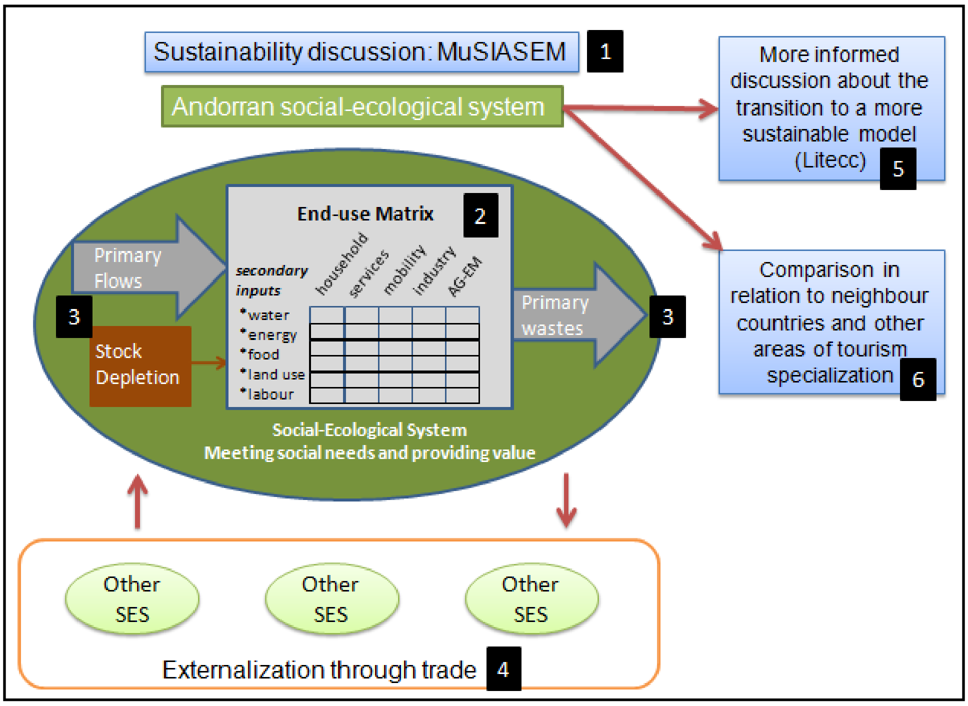


Figure 3. Research Objectives.

In order to tackle the abovementioned main research objective, the following questions and specific sub-objectives must be considered (see also figure 3):

Question 1: How does the MuSIASEM approach frame the sustainability discussion?
Sub-objective 1: Synthesize and discuss the theoretical foundations of the methodology, aligning them within the general framework of ecological economics.

Question 2: How are the metabolized flows (water, energy, food) used by the different societal compartments in Andorra?
Sub-objective 2: Characterize the flows metabolized by the Andorran system through the construction of a multi-level, multi-dimensional end-use matrix to determine the amount and rate of secondary inputs required for sustaining and reproducing the activities carried out in Andorra.

Question 3: What pressure do the metabolized flows created on the environment (in terms of requirement of primary flows and primary wastes)?

Sub-objective 3: Characterize the amount and rate of primary flows and primary wastes required from and dumped in the environment through the construction of an environmental pressure matrix to determine the pressure that the metabolized flows generate on the environment.

Question 4: How open is the Andorran social-ecological system? To what extent does it rely on international trade to externalize (outsource) the production of secondary inputs and environmental pressures and impacts to other SES?
Sub-objective 4: Analyze the level of openess of the Andorran system through the construction of an externalization matrix in order to assess the degree of displacement of environmental pressures to other SES.

Question 5: How the results of the MuSIASEM-WEF nexus analysis contribute to have a more informed discussion in relation to the current policy discourse incorporated in law Litecc?
Sub-objective 5: Reconceptualise the concept of energy sovereignty and the use of the energy intensity indicators considering the special situation of Andorra to have a more informed discussion in relation to the transition to a more sustainable model.

Question 6: How are the metabolic characteristics of Andorra compare with those of neighbour countries and other areas of high tourism specialization?
Sub-objective 6: Make a metabolic comparison of Andorra in relation to France, Spain, the average of the European Union and the island of Menorca in order to show the data obtained for Andorra in relation to other countries.

5. MUSIASEM applied to Andorra.

The following subsections describe the application of MuSIASEM to the case of Andorra including a brief contextualization information about the country, pre-analytical choices, the data used in the analysis (up to the current state of the research) and some limitations.

5.1. Contextualization.

Andorra is a small and mountainous country (77.536 inhabitants in 2019) enclosed in the Pyrenees Mountains between France and Spain. The evolution of the population has been exponential in the country. In 1947 Andorra had only 5.385 inhabitants (figure 4). Rapid economic development and high immigrations rates in the second half of the 20th century explains this increase (Miquel et al., 2021). Moreover, Andorra is one of the few countries in the world where the population with Andorran nationality (48,7%) is smaller than the population of residents with non-Andorran nationality (51,3%) (Centre de Recerca Sociològica, 2018a).

At the present, approximately 39% of the country's territory is covered by forest, while infrastructure and urban areas account for only 3% of it. Agriculture activities are mainly found in the valleys. However, the agricultural sector, based on a traditional farming management system, plays an important role providing a large number of environmental services, particularly in landscape conservation. For a better understanding, figure 5 shows the map of land uses in Andorra.

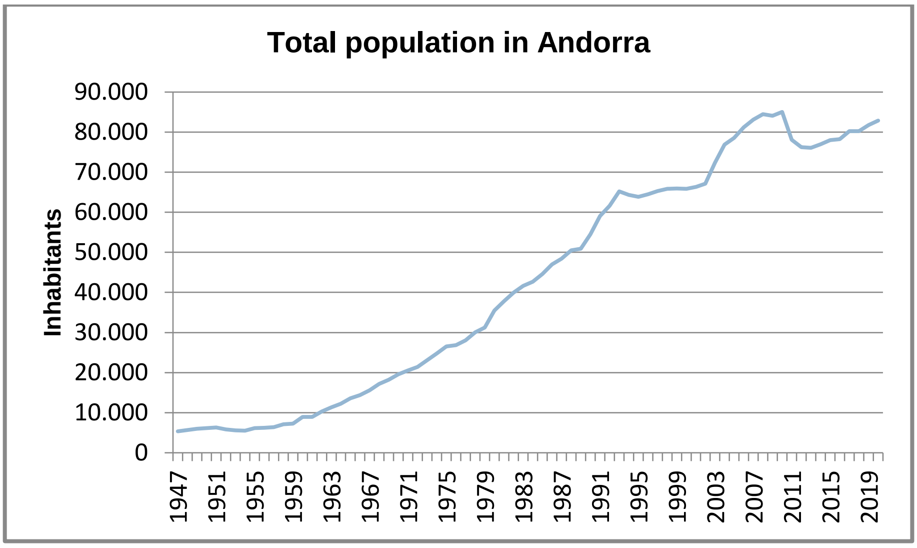


Figure 4. Evolution of the Andorran population. Source: www.estadistica.ad

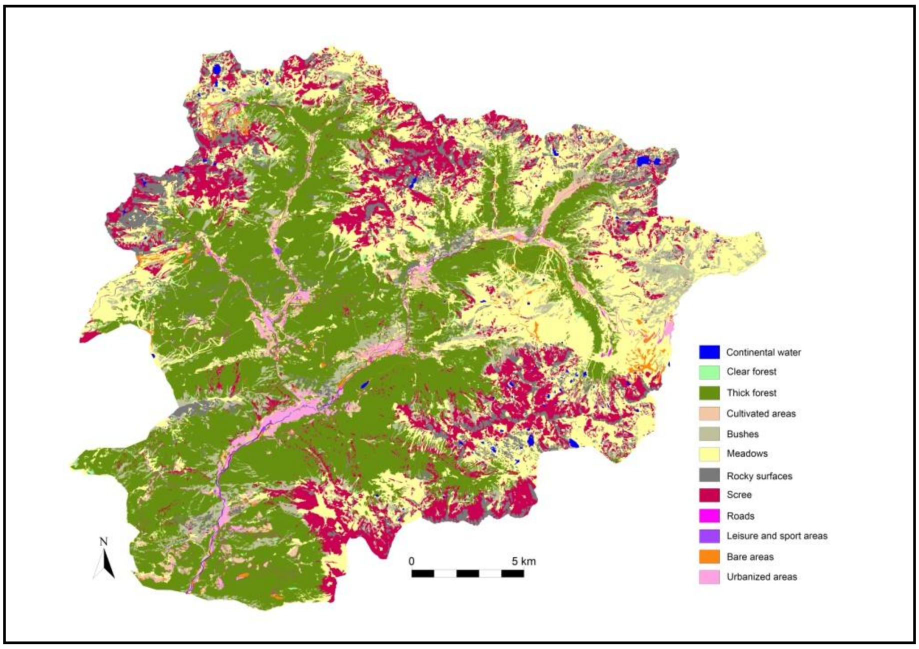


Figure 5. Map of land covers. Source: (Cenma-IEA, 2012a)

The industrial sector remains quite limited representing 3,4% of GDP in 2019. The Andorran economy is mainly focused in tertiary activities. Services is the most important sector of the Principality's economy regarding 86,1% of the country business and 87,7% of the employees. Thus, tourism is one of the fundamental pillars of the Andorran economy, directly or indirectly responsible for 85% of GDP with about 8 million visitors per year. In winter, products related to skiing are predominant with 2,5 million skiing days sold (2017-2018 season) distributed over more than 3.200 ha of skiing surface. The snow sector is the pillar of 2.000

workplaces, but is very vulnerable to climate changes and to the rise of the hydrocarbon prices, given that road networks are the only link with neighbouring countries (Miquel et al., 2021).

5.2. Pre-analytical definitions.

- Constituent components.

Initially, the following functional compartments and sub-compartments will be considered for the study of the Andorran system: the whole (n), paid work sector (PW, n-1) and the household sector (HH, n-1). Within the PW compartment we define three economic sectors: (i) agricultural sector (AG), including agriculture, livestock and fish farming; (ii) the industrial sector (ICM), including the energy, industry, construction and manufacturing activities; and (iii) the service sector (SG), including services and government activities. The analysis is expected to gain in hierarchical depth by characterizing *metabolic processors* for the hotel sector and skiing areas.

Transportation is another functional sector that has to be properly defined. As functional compartment, it includes human activity belonging to the HH sector (the use of private car and motorcycles) and PW sector (in the public transportation sector in services and in other economic activities in paid work). In this study, starting from the data of Travesset-Baro (2017), energy consumption in transport has been assigned to the HH and PW sectors discounting the item corresponding to fuel tourism, i.e. the fuels purchased by tourists and same-day visitors when shopping in Andorra.

- Definition of fund elements.

The size of the fund HA (measured in hours per year) and the size of the fund element LU (measured in hectares per year) are considered to characterize the constituent components of Andorra. Both categories, represented in figure 6, are used to measure the size of functional compartments and sub-compartments (i.e. parts and parts of the parts) of the system defined across different hierarchical levels of organization.

Data about land uses for this study has been extracted from the latest land use map of Andorra (CENMA-IEA, 2012a). Percentages calculated from the "authorized area" data (Departament d’Estadística, 2019a) have been applied to disaggregate the information from the land cover map between the different functional compartments (see appendix 3 for more information about how the numbers have been produced). The data about the total human activity, expressed in hours/year, has been calculated by summing: (i) the activity of the permanent residents; (ii) the activity of temporary and cross-border workers; (iii) the activity of tourists (staying overnight) and same-day visitors. This distinction is necessary for properly characterizing an open system such as Andorra in which the characteristics of the flows (money, energy, water, food) does not depend only on the activities expressed by the permanent residents. The calculation of the equivalent population was carried out according to (Departament de Medi Ambient, 2016a). The data about paid work is based in the information presented in (Centre de Recerca Sociològica, 2018a). The calculation considers all contracts as full-time contracts with an annual maximum of 1.800 hours worked following the *Codi de Relacions Laborals* (Llei 35, 2008)[4]. The extra hours per year have also been included in the assessment. This assessment underestimates the number of hours worked because: (i) a certain amount of informal work is not taken into account (Iglesias-Pérez et al., 2018); (ii) there is a high degree of precarious employment in economies based on the tourism sector (Cañada, 2018); and (iii) the work carried out by foreign companies in Andorra has not been taken into account.

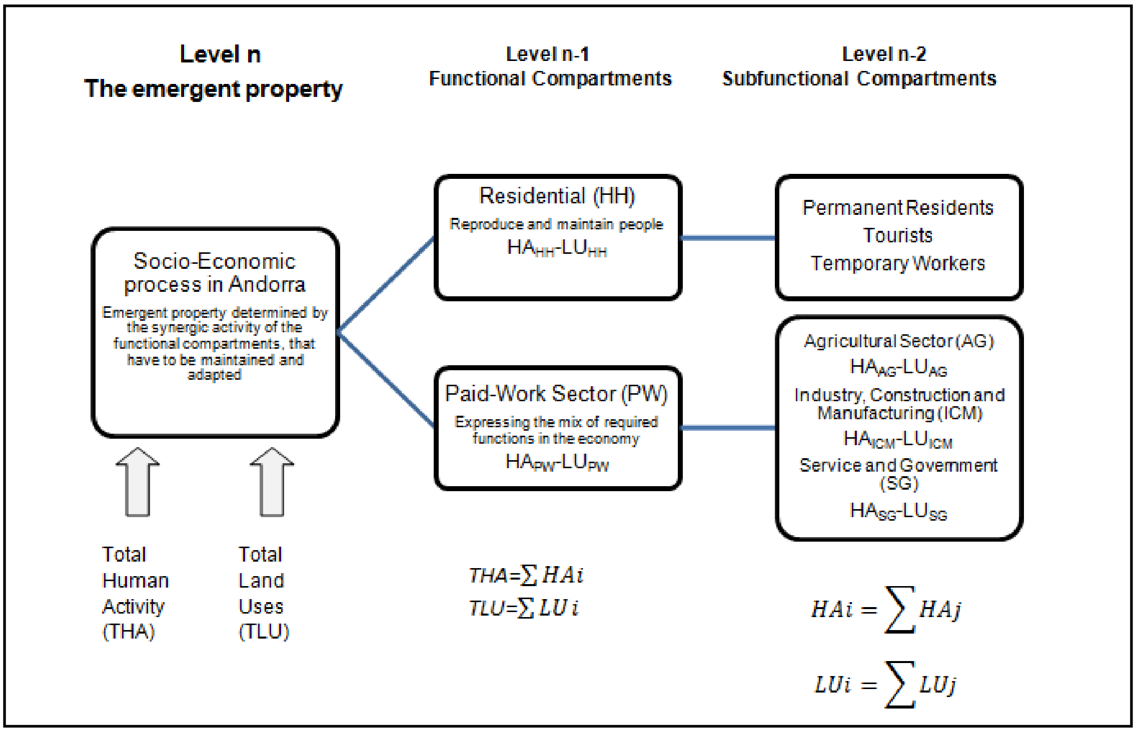


Figure 6. Hierarchical organization of the levels in the system.

The categories defined in figure 6 refer only to socio-economic processes in Andorra. However, there are ecological funds (e.g. forests, meadows, aquatic ecosystems), whose activities of self-organization are outside human control. These provide with services and therefore have to be considered. The analysis of these funds is important to assess environmental impacts. In this study the size of ecological funds is mapped in terms of the land fund "non-managed land" (NML). This category includes land covers, such as forest, rocky areas or rivers, that supply environmental services that people in Andorra (an tourists) can use, but whose characteristics do not depend directly on human intervention (even though they may be affected by it). The activity of these ecological funds may have

[4] Available at this link

a significant effect on the quality of life of the people of Andorra (e.g. carbon sinks, water cycle, aesthetic aspects and cultural identity) or may affect economic sectors, such as tourism.

- Definition of flow elements.

Table 2 summarizes the different categories of the flow elements to be considered for the characterization of the metabolic pattern of Andorra.

In this early stage (section 6) six flows elements have been considered: electricity (in GWh), electricity in thermal equivalent (in TJ), fuel (in TJ) and processed heat (in TJ) —as *energy carriers*; *energy throughput* (ET) expressed in *gross energy requirement* (GER); and cubic meters of blue water (keeping the distinction between consumptive and non-consumptive use). In order to establish a bridge between biophysical and monetary variables the accounting of the flows of gross added value of economic sectors has been also considered. Moreover, a simplified assessment based on direct carbon emissions associated to final consumption of the different functional compartments in Andorra and a quantification of the waste generated at the n level have been calculated. It is planned to carry out a more detailed assessment including not only the requirements of exosomatic energy but also the requirements of endosomatic energy (food) and the breakdown of the mix of *primary energy sources* needed to generate the secondary inputs of energy carriers in later phases of the research.

Table 2. Categories of flow elements for the characterization of the metabolic pattern in Andorra.

	Primary Flows	**End Uses**	**Primary Wastes**
Energy	Water Hard Coal Lignite Oil Gas Uranium	Electricity Heat Fuel GER	Emissions
Food	Water Arable land	Vegetable Grain Oil Animal	Nitrogen (N) Phosphorus (P) Potassium (K)
Water		Blue water consumption Blue water non-consumptive use	
Solid waste			Solid waste
Money		Money	

- Definition of the metabolic characteristics.

Regarding the metabolic characteristics in relation to dissipation, the following intensive variables have been established in this initial approximation: exosomatic metabolic rate (EMR) per unit of human activity, *exosomatic energy metabolic density* (EMD) per unit of land use, *water metabolic rate* (WMR) per unit of human activity, and water metabolic density (WMD) per unit of land use. The intensive variables economic labour productivity (ELP) and *economic land use productivity* (ELUP) have also been considered in relation to the metabolic characteristics of economic productivity.

- Data gathering.

The application of the methodology in the current state has been based primarily on a top-down approach. However for the analysis of the energy requirements of the HH sector, a bottom-up analysis has been carried out based on Travesset-Baro (2017). Table 3 summarizes the variables considered and data sources. The interested reader can refer to the glossary at the end of this document for more detailed definitions and the corresponding annexes to check how numbers have been generated.

5.3. Diagnosis.

Research work should make it possible to account the entanglement over the different components of the WEF nexus across levels, scales and dimensions of analysis. The construction of an EUM matrix and an EPM matrix together generates a complete diagnosis of the metabolic pattern of the Andorran system. These determine how energy carriers, food products and water quantities used inside the various constituent components of the Andorran system are related to the quantity of primary sources required to generate the inputs and the quantity of primary sinks required to absorb the resulting wastes. Moreover, primary flows —coming either from a non-renewable (stock depletion) or renewable (fund-flow supply) resources— and primary wastes —dumping into the biosphere in a sustainable (flow-fund sink) or unsustainable (sink filling) way— will be characterized.

This diagnosis should also be able to show the crucial role played by imports (*externalization*) in supporting the wealth of Andorra. The option of importing allows Andorra to ease both the internal requirement of economic production factors (by avoiding the labour and technology required for the production of the imported goods and therefore overcoming potential viability constraints) and environmental pressures (by avoiding the local use of natural resources and sink capacity for the production of imported goods and therefore overcoming potential feasibility constraints). Externalization through imports will be analyzed for food and energy products. For its characterization, a notional set of "virtual processes" will be defined using benchmarks of end-uses and environmental pressures (Giampietro et al., 2020). Labour requirements associated with imported manufacturing goods —human time is a crucial and overlooked societal limit— will also be estimated calculating "virtual workers" (Pérez-Sánchez et al., 2020).

Table 3. Extensive and intensive variables considered and sources.

	Abbreviation (Variable)	Definition and units	Sources
	Fund elements used to assess the size of constituent components		
	HA (Human Activity)	Time in, in hours (h) devoted to each level on analysis	-CRES (2018) -Departament de Medi Ambient (2016a)
	LU (Land Uses)	Area, in hectares (ha) devoted to each level of analysis	-CENMA-IEA (2012a) -Departament d'Estadística (2019a)
	Flow elements used to assess the metabolic pace of constituent components		
Extensive Variables	GVA (Gross Value Added)	Value, in EUR millions (M€) of goods and services produced in each level of analysis	-Departament d'Estadística (2015)
Extensive Variables	ECi (Energy Carrier)	Amount of every type of energy, i, used in each level of analysis (GWh for electricity and TJ for thermal energy and liquid fuels) Types of energy considered: (i) electricity (E); (ii) fossil fuels used as Fuel (F) and fossil fuels used for heating (H)	-Travesset-Baro (2017) -Miquel et al. (2014) -Departament d'Estadística (2019b)
Extensive Variables	GER (Gross energy requirement)	Equivalence in TJ for E (x 2,61), F(x1,38) and H (x1,10). Assuming that fossil energy is used to produce the different energy carriers (Partial Substitution Method)	-Giampietro et al. (2013)
Extensive Variables	WT (Water Throughput)	Amount of blue water used in each level of analysis (m³)	-Departament de Medi Ambient (2016b)
Extensive Variables	CEi (Carbon Emissions)	Amount of CO_2 eq emissions for type of energy, i, used in each level of analysis Types of energy considered: (i) electricity (E); (ii) fossil fuel used as Fuel (F) and fossil fuel used for heating (H)	-Miquel et al. (2014) -Travesset-Baro (2017)
Extensive Variables	SW (Solid Waste)	Amount of solid waste generated for the whole of the socio-ecological system under analysis	-Departament de Medi Ambient (2016a)
	Metabolic characteristics in relation to dissipation		
Intensive Variables	MR (Metabolic Rate)	Flow/HA: Amount of flow (ECi, GER or WT) per unit of human activity (HA) devoted to each level of analysis (unit/h)	
Intensive Variables	MD (Metabolic Density)	Flow/LU: Amount of flow (ECi, GER or WT) per unit of land use (LU) devoted to each level of analysis (unit/ha)	
	Metabolic characteristics in relation to productivity		
Intensive Variables	ELP (Economic Labour Productivity)	GVA/HA: Gross value added (in nominal terms) per hours of human activity in each level of analysis (€/h)	
Intensive Variables	ELUP (Land Use Productivity)	GVA/LU: Gross value added (in nominal terms) per hectare of land use in each level of analysis (€/ha)	

In short, the research work in this stage should generate a complex diagnosis (beyond an analysis based on a dimension and scale) relevant to discuss a more sustainable model, i.e. a low carbon economy in Andorra.

5.4. Sustainability discussion.

The more holistic contextualization of the previous point can be used to assess the applicability in Andorra of ideas that are gaining social acceptance in the sustainability debate. Therefore, a more informed discussion of concepts and indicators included in law Litecc can be raised in relation to:

1. The problematic assumption of considering the energy intensity indicator as a valid indicator to measure sustainability improvements in Andorra (Fiorito, 2013; Velasco-Fernández et al., 2020a). The energy intensity indicator is a flow-flow one that should be better contextualized under a flow-fund analysis, i.e. energy intensity may decrease while environmental pressures and ecological deterioration increase.
2. The plausibility of efforts to great energy sovereignty —when considering both endosomatic and exosomatic energy we may find out that it is not possible to internalize the production of primary flows and secondary inputs that are at the moment imported (Renner et al., 2020a; Ripa et al., 2021). In this sense, it is possible to modulate the restrictive use made in the political discourse of the concept energy sovereignty to reflect on the deep biophysical interdependences of Andorra with other SES.

6. Provisional results and discussion.

This section presents and discusses the diagnostic results of the analysis of the metabolic pattern of Andorra. The focus on this analysis has been to develop a first EUM for energy and water and partially de EPM for CO_2 emissions and wastes. Rows show the hierarchy levels of analysis (e.g. n, n-1, n-2, etc.) and columns the different elements considered. Note that the rounding of significant digits might modify the sum among columns in some cases. The expression of a certain metabolic pattern is both *impredicative* and context-dependent. Socioeconomic systems express different metabolic patterns according to their internal organization that is affected by changes in boundary conditions. Therefore, it is essential to compare the findings of this study in Andorra against reference values or benchmarks —established in MuSIASEM literature thanks to long-term analysis (Giampietro et al., 2013, 2012)— or values from other countries. In this sense, after the diagnostic phase, a basic comparison is made with reference to neighbouring countries from information obtained in Velasco-Fernández (2017). Moreover, the results obtained are discussed comparing them with those of another eminently tourist system such as the island of Menorca (Marcos-Valls et al., 2020).

6.1. Fund elements used to assess the size of constituent components.

Table 4 shows the available information about HA and LU of Andorra during a year period (the reference year is 2015). This information on the fund elements considered is the basis for the subsequent calculation of the metabolic and economic relations collected in the subsequent tables.

Table 4. Characterization of the constituent components of Andorra at different level of analysis.

Constituent components	HA(Mh[a])	LU (ha[b])
N Andorra	**894**	**46.770**
N-1		
Household (HH)	600	472
PW	75	6.465
Other users[c]/NML[d]	219	39.833
N-2 (PW)		
AG[e]	1	2.058
ICM[f]	9	337
SG[g]	65	4.070

[a]Mh: Million of hours; [b]ha: hectares; [c]Other users: tourists not staying in private residence and one-day visitors; [d]NML: Non-Managed Land. [e]AG: agriculture; [f]ICM: industry, construction and manufacturing; [g]SG: service and government. Sources: Elaboration of data from CRES (2018); Departament de Medi Ambient (2016a); CENMA-IEA (2012a) and Departament d'Estadística (2019a).

If we consider Andorra as an *autopoietic system* (Maturana and Varela, 1980), i.e. an integrated whole inseparably linked to metabolic and dynamic processes of change, we can observe how the maintenance of the identity of Andorra depends on biophysical elements that come from outside its political borders. Data about HA shows that the visiting population (tourists and one-day visitors) represent 24% of the total, taking into account a "population equivalent" of 102.045 people (Departament de Medi Ambient, 2016a). Moreover, temporary workers (included in the HH and PW sectors) represent an important part of the workers for the Andorran economy reaching percentages of more than 50% of the hours worked per year in key sectors, such as the hotel sector, in the winter season (Centre de Recerca Sociològica, 2018a). Around 92% of the total hours of human activity in Andorra are devoted to non-paid activities categorized as households and other users and just 8% is dedicated to PW activities. The percentage of human time in paid work of 8% of Andorra is slightly lower compared with the 12% of Barcelona (Pérez-Sánchez et al., 2019) and the 10% in Catalonia (D'Alisa and Cattaneo, 2013). According to the theoretical concept of *dynamic energy budget*, there must be a balance between the energy and materials required to express the various societal functions and the supplied flow generated by the primary and secondary sectors (Giampietro et al., 2020). The low proportion of PW time in Andorra which, as we will see, is similar to that of the surrounding countries, indicates that this metabolism system is highly dependent on imports and externalization of productive activities. This is corroborated when verifying the distribution of working time between the economic sectors. The SG sector accounts for 87% of the working hours. This sum is above the value of 81% of Barcelona and well above of Catalonia (65%). This analysis flags the importance of tourism in the economy. The metabolic system of Andorra is typical of a tourism-driven system.

Table 4 also displays information about the land uses. Andorra is a mountainous country with a total area of 46.770 ha of steep terrain. This explains the fact that 85% of the territory is considered non-managed land. According to the land cover map (CENMA-IEA, 2012a), only 1,51% of the territory corresponds to urbanized areas. Based on estimated percentages from data on area authorised for construction (Departament d'Estadística, 2019a), from the total land area of Andorra, 1% is devoted to urban and residential areas, that is, it is used for HH activities. Economic activities, i.e. PW, use 13% of the land much of which goes to the SG sector (63%), followed by the AG sector (32%) and with a residual character the ICM sector (5%).

6.2. Economic Variables.

Table 5 presents economic data relative to paid work activities in Andorra from data available in Departament d'Estadística (2015).

Table 5. Gross Value Added for the different economic activities in Andorra and economic productivity per unit of hour of labour (ELP) and per unit of area devoted to each sector (ELUP).

Economic Variables	GVA (M€[a])	ELP (€/h)	ELUP (€/ha)
N Andorra	**2.288**	**2,6**	**48.926**
N-1			
Household (HH)			
PW	2.288	30,7	353.944
N-2 (PW)			
AG	12	19	5.792
ICM	248	27	735.813
SG	2.028	31	498.349

[a]M€: EUR Millions. Source: Elaboration on data from Departament d'Estadística (2015).

In absolute terms, the SG sector accounts for the higher share of the *gross value added* (GVA) of Andorra, 88%, dominated by tourism and financial activities, followed by the ICM sector (11%). The AG sector, basically focused on tobacco growing and livestock activities represents only 1% of the total. However, this analysis of the negligible role of agriculture does not consider other functions such as the preservation of traditional landscape and traditional identities (home gardens). When looking at economic productivity we can find a similar trend. The SG sector generates the highest monetary flow per hour worked, closely followed by the ICM sector (where sensitive activities with high value added are included, such as the generation and distribution of electricity), with agriculture being the last. In terms of land use, the economic land use productivity (ELUP) shows that the industrial sector produces more than 125 times EUR per hectare than the agricultural sector and almost 150% more than services. As we will see, in general terms these high productivities of the factors of production (labour and land) are the result of a high reliance on fossil fuels with the consequent dependence on external resources. This indicates that Andorra is an open metabolic system, whose economic activities are not determined by the availability of resources inside the physical boundaries of the country.

6.3. End-Use Matrix for energy.

6.3.1. Profile of energy types: extensive variables.

Table 6 presents the values of total energy throughput used in Andorra at different levels of analysis. Note that for the domestic sector it has been possible to break down the requirements of different functions within the household. The transformation of the different energy carriers (Electricity, Heat and Fuel) into the corresponding amount of gross energy requirement has been done by applying the "*partial substitution method*" (Giampietro et al., 2013).

The analysis of the total energy throughput at the level of the whole country (n) considering equivalent thermals units for the three energy types —electricity (E), fuels (H) for heating and fossil fuels (F)— shows a predominant use of E, 53% (measured in its gross energy requirements in thermal equivalent) followed by F (27%) and, finally H (20%). It should be noted that the difference between the measurement of electricity in kWh and the measurement in thermal energy depends on the loss associated with the conversion of Joule of primary energy sources into Joule of electricity. At a lower level of analysis (n-1), the total requirements (GER) are distributed fairly evenly between the HH sector (45%) and the PW sector (55%). The analysis of the different energy types for HH and PW reflect the dominance of F with 52% of the total in the HH sector while PW is dominated by electricity, 69% of the total. We can find a reason for the high consumption of F in the HH sector in the massive use of the private vehicle both in internal (within the borders) and external (outside the borders) movements due to the low implementation of public transport and the lack of alternative options such as train or plain. The automobile fleet is responsible of an average of 862.000 kilometres per day in Andorra (Miquel et al., 2014). At level n-2, the breakdown carried out for the HH sector allows determining the sub-functional compartments that require higher energy consumption (in bold): private mobility, heating and household electrical appliances. In the productive sectors, as expected, the highest consumptions correspond to the SG sector with a preponderance of electricity consumption (hotel industry, department stores, ski slopes, etc.).

Table 6. End Use Matrix. Energy Throughput in Andorra.

Energy Throughput (ET)	Electricity (GWh[a])	Electricity (T.E. TJ[b])	Heat (TJ)	Fuel (TJ)	GER[c] (TJ)
N Andorra	**547**	**5.140**	**1.874**	**2.571**	**10.750**
N-1					
Household (HH)	140	1.314	607	2.089	4.865
PW	407	3.826	1.267	482	5.885
N-2 (HH)					
Heating	26	247	512		**810**
Sanitary hot water	14	133	95		238
Air conditioning	2	18			18
Lighting	10	90			90
Cooking	21	198			198
Household electrical	67	628			**628**
Private mobility				2.089	**2.883**
N-2 (PW)					
AG	Negligible	Negligible	Negligible	0,4	1
ICM	12	113	35	39	205
SG	395	3.713	1.232	443	5.679

[a]GWh: Gijawatt hours; [b]T.E. TJ: Thermal equivalent Terajoule. [c]GER: Gross Energy Requirements= Electricity T.E +1,1*Heat+1,38*Fuel). Deep blue colors indicate higher values. Source: Elaboration on data from Travesset-Baro (2017); Miquel et al. (2014) and Departament d'Estadística (2019b).

6.3.2. Metabolic relations: intensive variables.

Metabolic ratios make it possible to identify the energy requirements per hour of human activity (EMR in gray) or per hectare (EMD in reddish color) which, given the available technology and a determined set of social practices, are required to guarantee the functionality of the different societal compartments and the reproduction of the whole system (table 7).

In the case of Andorra the highest EMR corresponds to the service sector, being very intensive especially in the use of electricity. The lower intensity in the use of energy in the ICM is connected with the fact that industrial sector in Andorra includes very labour-intensive manufacturing such as jam and cheese manufacturing establishments or plumbing and construction companies. The agricultural sector, given its traditional and marginal character, does not have data available at the statistical level, so a bottom-up approach is necessary in order to characterize the sector from the analysis of its structural elements (farms and processes of crop production at the field level). The lowest value of the EMR of the industrial sector compared to the service sector represents an anomaly compared to other metabolic studies using MuSIASEM and indicates the lack of heavy mechanical industries (Velasco-Fernández, 2017). In relation to the PW sector, the HH sector is almost ten times less energy intensive. This is understandable if we keep in mind the high percentage of hours of human activity devoted to the HH sector, where sleeping and leisure reduce the energy consumption per hour.

Table 7. End Use Matrix. Metabolic Relations in Andorra.

EMR[a] EMD[b]	E[c] kWh/h	E T.E.[d] MJ/h	H[e] MJ/h	F[f] MJ/h	Total EMR MJ/h	E MWh/ha[g]	E T.E. GJ/ha[h]	H GJ/ha	F GJ/ha	Total EMD GJ/ha
N Andorra	**0,6**	**5,7**	**2,1**	**2,9**	**12**	**12**	**110**	**40**	**55**	**230**
N-1										
HH	0,2	2,2	1	3,5	8,1	296	2.785	1.287	4.428	10.311
PW	5,5	51,3	17	6,5	78,9	63	592	196	75	910
N-2 (PW)										
AG	n.a	n.a	n.a	0,6	0,9	n.a	n.a	n.a	0,2	0,3
ICM	1,3	12,1	3,8	4,2	22	36	334	104	115	606
SG	6,1	57,4	19,1	6,8	87,9	97	912	303	109	1.395

[a]EMR:Energy Metabolic Rate; [b]EMD: Energy Metabolic Density; [c]E kWh: Electricity kilowatt hour; [d]E T.E MJ/h: Electricity Thermal Equivalent Megajoule hour; [e]H MJ/h: Heat Megajoule hour; [f]F MJ/h: Fuel Megajoule hour; [g]MWh/ha: Megawatt hour per hectare; [h]GJ/ha: Gigajoule hour per hectare. Source: Elaboration on data from Travesset-Baro (2017); Miquel et al. (2014) and Departament d'Estadística (2019b).

The comparison of the energy metabolic density (EMD) profiles for each functional compartment shows the high energy use per hectare in the HH sector. Andorra has a high population density for the scale of the Pyrenees (163 inhabitants/km^2). When considering only the urbanized surface the density reaches 10.000 inhabitants/km^2 (Miquel et al., 2014). This is due to the massive presence of multi-store buildings in which the residential area inside the apartments is a multiple of the external area occupied by the building. Such high densities can only be achieved by importing resources from outside (based on a stock-flow model) feeding the consumption of high density buildings. It would be impossible to achieve these densities if the flows of food, energy carriers and consumable products had to be generated by using only the resources available in Andorra (fund-flow model). Thus, the values of EMD contribute to defining Andorra as an open metabolic system, whose metabolic rates are determined partially by the activities carried out within the system and partially by the externalization of its economic activities and metabolic requirements.

6.4. Profile of water used in Andorra: EUM for water.

Table 8 displays information on water consumption and metabolic relations in Andorra based on Departament de Medi Ambient (2016b). The different uses of water are classified into consumptive and non-consumptive uses. The former includes extraction of water and its return to the environment in a different place with loss of quality and/or quantity (e.g. domestic, recreational and agricultural uses). The latter includes abstraction of water without modifying its quantity and quality. In the case of Andorra, these primarily include the use of water for the generation of electricity (ICM sector) and for the creation of artificial snow (SG sector). Metabolic rates, i.e. Water Metabolic rate (WMR) and Water Metabolic Density (WMD) are calculated only for consumptive uses. The distribution of the *water throughput* used in Andorra in consumptive uses at level n-1 shows that the economic activities (PW) take 58% of the total, while residential activities (HH) use 42% of the total. Within the economic activities, level n-2, the service sector (SG) represents 78% of the water, followed by agriculture (mainly by growing tobacco — 22%).

Table 8. End Use Matrix of water use in Andorra.

Water Throughput (WT) Water Metabolic Rate (WMR) Water Metabolic Density (WMD)	Total Water Throughput (Mm³)[a]	Consumptive use (Mm³)	Non-consumptive use (Mm³)	Water Metabolic Rate Consumptive Use (m³/h)	Water Metabolic Density Consumptive Use (m³/ha)
N Andorra	**90,2**	**13,2**	**77,0**	**0,01**	**282**
N-1					
Household (HH)	5,5	5,5		0,01	11.756
PW	84,6	7,6	77,0	0,10	1.180
N-2 (PW)					
AG	3,0	1,7	1,3	2,73	847
ICM	74,5	0,02	74,5	0,002	64
SG	7,1	5,9	1,2	0,09	1.441

[a]Mm^3: Mega cubic meters. Source: Elaboration on data from Departament de Medi Ambient (2016b).

The industrial sector (ICM) represents a marginal percentage of the water throughput for consumptive uses. However, it uses a very important fraction of non-consumptive uses (88%) with the generation of electrical energy. Households are very intense in the use of water per hectare (WMD), 11.756 m3/ha but very low if we study the amount of water per unit of time (WMR), 0,01 m3/h. This is because household activities cover 92% of the total time in Andorra and occupy just a very small fraction of the land cover. The distribution of the percentages of water withdrawal for urban (including household and services), agricultural and industrial uses is diverse across countries according to data from AQUASTAT (FAO, 2019). The profile for Spain, for instance, is 14%, 67% and 19%, with agriculture having the main use, similar to Catalonia, while the profile of Germany is 78%, 2% and 20%, clearly dominated by urban uses. In Andorra the amount of water for urban uses (consumptive use) reaches a percentage of 86%. Therefore, the pressure on water for urban uses is high, influenced by seasonality, including temporary residents and tourists activities (Reynaud et al., 2018). Moreover, considering only residents and urban uses, Andorra has a record number of water consumption reaching a figure of 382 litres/day/resident (Departament de Medi Ambient, 2016b) much higher than the European average of 128 litres/day/person (Aquae, 2020). It should be noted, however, that probably this value is not due to high levels of final consumption but rather to a high level of losses in the supply network.

6.5. Environmental pressures: emissions of CO_2 and generation of wastes.

Table 9 illustrates the environmental pressure connected to the energy flows in Andorra. In this preliminary quantitative phase, the emissions of CO_2 for the different societal compartments have been considered. The generation of waste has also been estimated for the level n. In a later phase, and for a more complete characterization, it will be necessary to account for the requirements of primary energy sources and also land and water requirements for the production of food consumed in Andorra. The calculation of emissions has been carried out mainly from Travesset-Baro (2017, p. 47). In this sense, the origin of the imported electricity and its corresponding emissions factors have been calculated using flat rates (Spain: 302gCO_2/kWh; France: 44gCO_2/kWh). It is important to note that for the reference year (2015) only 17% of the electricity consumed in Andorra is of autochthonous origin (hydroelectric generation, burning of waste and a residual fraction from photovoltaic solar energy). Finally, emissions from agricultural and livestock wastes have been included in the label "Others" (Miquel et al., 2014). Regarding the waste throughput, it has not been possible to obtain data for the different functional sub-compartments, but it has been possible to segregate on the different destinations of the waste generated (Departament de Medi Ambient, 2016a).

The analysis at the level n, the whole socioeconomic system of Andorra, shows that the main energy carrier generating emissions are fuels (46%) and fuel for heat (30%), both coming entirely from imports. At the lower levels, n-1 and n-2, present the HH sector as the higher net contributor to CO_2 emissions (49%), followed by the SG sector (43%). A deeper analysis of the HH sector reveals that the form of energy carrier associated with more emissions is F (67%) due to the massive use of private vehicles. The SG sector, for its part, has a higher level of emissions due to the use of diesel for heating. It is important to highlight that emissions from transport companies performing services in Andorra are not included in the SG sector. In the case of considering their inclusion, emissions from the energy carrier "fuel" would be significantly higher. Regarding the generation of waste, a relevant part (29%) is used as an input for the energy sector (in ICM). The rest is exported for treatment or elimination generating environmental pressures on other SES.

Table 9. Environmental Pressure Matrix for emissions and waste inside Andorra.

Carbon Emissions (CE) Waste (W)	Electricity (tCO_2eq)[1]	Heat (tCO2eq)	Fuel (tCO2eq)	Others (tCO2eq)	Total (tCO2eq)	Elimination (t)[2]	Energy recovery (t)	Recycling (t)	Other valuations (t)	Preparing for reuse (t)	Total (t)
N Andorra	**108.875**	**141.795**	**193.149**	**5**	**466.424**	**2.280**	**34.087**	**26.221**	**50.390**	**1.026**	**114.004**
N-1											
Household (HH)	27.835	47.342	154.362		229.539						
PW	81.040	94.453	38.787	5	236.885						
N-2 (PW)											
AG	n.a	n.a	2.571	5	25.176						
ICM	2.382	2.603	2.923		7.908						
SG	78.658	91.850	33.293		203.801						

To the energy sector

[1]tCO_2eq.: tons of CO_2 equivalent; [2]t: tons. Source: Elaboration on data from Travesset-Baro (2017), Miquel et al. (2014) and Departament de Medi Ambient (2016a).

6.6. Deepening the level of observation: the hotel industry functional sub-compartment in Andorra.

Based on data from statistics (Departament d'Estadística, 2015) and data about resource consumption (Travesset-Baro 2017, Miquel et al., 2014), the methodology allows characterizing one of the most important sector of the Andorran economic system, directly responsible for 8% of Gross Value Added and 13% of full-time employees: the hotel and catering sector. Moreover, a parallel accounting of the profile of allocation of human activity in the hotel and catering sector is introduced in the end-use matrix. Indeed, for many of the activities taking place in the service sector there is a simultaneous requirement of human activity both on the supply side (e.g. people working in a restaurant or bus drivers) and the demand side (e.g. customers of the restaurant or passengers riding on the bus). This novelty used in the accounting system allows the simultaneous characterization of the human activity paying in order to use the activities expressed by the hotel sector in the economy and the hours of human activity related to the paid work hotel sector. Table 10 shows the results.

Comparing the hotel and catering sector in Andorra with the reference values in the SG sector (level n-2), we observe a lower economic productivity per hour of work (ELP_{Hotel} of 19 €/h vs. ELP_{SG} of 31 €/h). However, given the compact and integrate nature of hotel activities, the sector has very high economic productivity per hectare (ELUP of over 2,5 million € per hectare vs. 0,5 million € per hectare of the SG sector). Moreover the hotel and catering sector presents metabolic rates and densities in energy and water requirements above the service sector average. Thus, the characterization generated illustrates the tension between economic productivity and environmental pressures. Although the production of space dedicated to hotels represents an important source of income for the Andorran economy, it also generates undoubted environmental pressures in terms of resource requirements. In a complementary way, the requirements per user of hotel establishments (tourists who do not spend the night in private residences), can be used to double check the viability of policies that seek to constantly increase the number of tourists and visitors to the country in relation to the resulting increase in externalization and environmental impacts.

Table 10. Analysis of the functional sector of hotel and catering in Andorra.

Level of Analysis n-3		
Constituent Components		
Human Activity	Ha (Mh)	9
Land Uses	LU (ha)	69
Economic Variables		
Gross Value Added	GVA (M€)	177
Economic Labour Productivity	EJP (€/h)	19
Economic Land Use Productivity	ELUP (M€/ha)	2,6
Energy Throughput (ET)		
Electricity (mechanic)	E (GWh)	92
Electricity Thermal Equivalent	E T.E. (TJ)	869
Heat	H (TJ)	712
Fuel	F (TJ)	n.a
Energy Metabolic Rate (EMR)		
Electricity (mechanic)	E (kWh/h)	10
Electricity Thermal Equivalent	E T.E. (MJ/h)	92
Heat	H (MJ/h)	76
Fuel	F (MJ/h)	n.a
Electricity (mechanic) users	Eu (kWh/h)	1
Electricity Thermal Equivalent users	E T.E.u (MJ/h)	5
Heat users	Hu (MJ/h)	4
Fuel users	Fu (MJ/h)	n.a
Energy Metabolic Density (EMD)		
Electricity (mechanic)	E (MWh/ha)	1.349
Electricity Thermal Equivalent	E T.E. (GJ/ha)	12.672
Heat	H (GJ/ha)	10.384
Fuel	F (GJ/ha)	n.a
Water Throughput (WT)		
Water throughput consumptive uses	WT (Mm^3)	2
Water Metabolic Rate (WMR)		
Water Metabolic Rate	WMR (m^3/h)	0,2
Water Metabolic Rate users	WMRu(m^3/h)	0,01
Water Metabolic Density (WMD)		
Water Metabolic Density	WMD (m^3/ha)	31.583

Source: Elaboration of data from Departament d'Estadística (2015); Miquel et al. (2014) and Travesset-Baro 2017.

The analysis carried out for the hotel sector will be complemented at a later stage with a characterization of the biophysical requirements of the ski areas using the analytical tool of a metabolic processor (Giampietro et al., 2020). Given the lack of statistical information, it will be necessary to characterize it using bottom-up information based on an analysis of structural elements and technical coefficients.

6.7. The metabolic performance of Andorra: characterization at level n.

Figure 7 synthesizes the metabolic performance of Andorra for the average society. A metabolic analysis complements the more conventional approaches (based on traditional economic narratives) adding relevant information such as the dependency on natural resources to perform economic activities that are often not included in the analysis. Figure 7 compares the resource requirements (energy, water, land), emissions of CO_2, waste and value added: (i) to generate 1 € of value added (economic performance); (ii) for each square meter of total land (land use performance); and (iii) for an hour of human activity considering the equivalent population of Andorra, i.e. including the activity of residents, tourists, one-day visitors and temporary workers (human activity performance).

Economic Performance	Land	0,2	m^2 per €
	Energy	5	MJ per €
	Water	6	l per €
	Emissions	0,2	kg CO_2 per €
	Waste	0,05	kg per €
Land Use Performance	Value Added	5	€ per m^2
	Energy	23	MJ per m^2
	Water	28	l per m^2
	Emissions	1	kg CO_2 per m^2
	Waste	4	kg per m^2
Human Activity Performance	Value Added	3	€ per h
	Energy	12	MJ per h
	Water	15	l per h
	Emissions	1	kg CO2 per h
	Waste	0,1	kg per h

Figure 7. Metabolic performance of Andorra at level n.

6.8. Comparison with neighboring countries.

The analysis of this section has been carried out on the basis of information for different European countries (for the year 2012) appearing in Velasco-Fernández (2017).

6.8.1. Fund element human activity.

Figure 8 shows the hours per capita assigned to the PW and HH sectors in Spain, France, the European Union and Andorra.

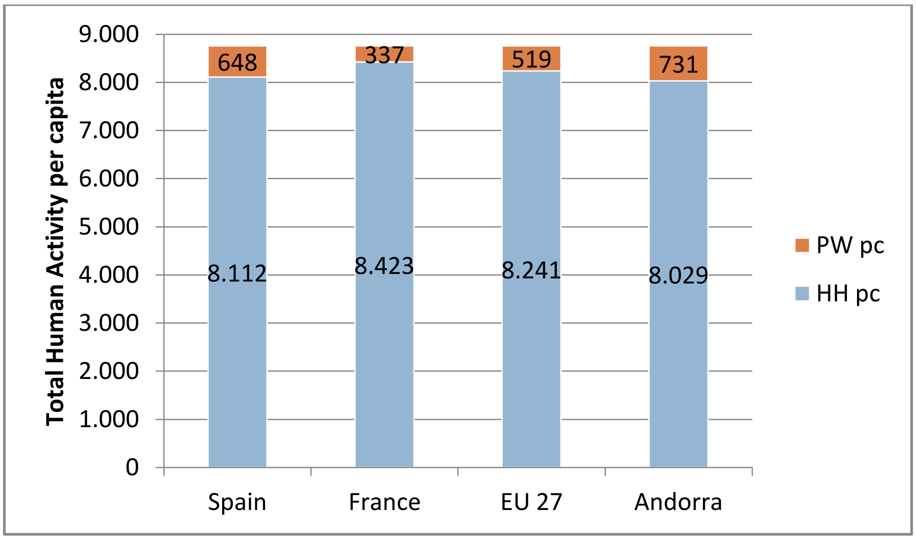


Figure 8. Hours per capita in Spain, France, the EU and Andorra. Source: Elaboration on data from Velasco-Fernández (2017) and CRES (2018).

The fraction of human activity invested in the Paid Work sector indicates the structural pressure on the productive population: the given supply of paid work has to sustain the material standard of living of the whole population. Andorra allocates around 8% of human activity to paid work (731 hours per capita of the 8.760 hours per capita per year available). This percentage is slightly higher than that of Spain (7%) and the European Union (6%) and is very similar to the average percentage for the years 2000-2016 of the European Union, which is around 8,5% (Velasco-Fernández et al., 2020b). In this sense Andorra is aligned with the European countries and can be considered a "mature" country, i.e with high social protection, pensions for people with disabilities and a high percentage of dependent population, in contrast to other countries facing structural changes and allocating a higher percentage of human activity to the paid work (e.g. China about 14,5%) (Velasco-Fernández et al., 2020b).

Regarding the allocation of hours per capita within the different productive sectors, figure 9 shows the high specialization of Andorra in service and government activities.

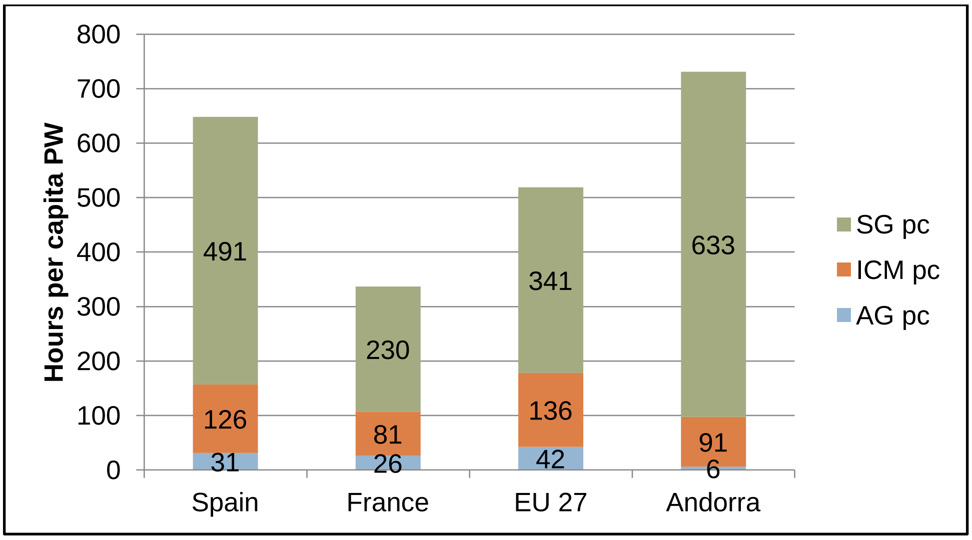


Figure 9. Hours per capita devoted to productive sectors in Spain, France, the EU and Andorra. Source: Elaboration on data from Velasco-Fernández (2017) and CRES (2018).

Andorra dedicates only 6 hours per capita of work to the AG sector compared to 31 in Spain and 42 in the European Union. This suggests the externalization of the production of the endosomatic energy requirements necessary for feeding its population. On the other hand, the high number of hours per capita invested in the SG sector (633 compared to 491 in Spain or 341 in the European Union) shows also another external dependence: that of tourists and one-day visitors who are necessary for the reproduction of the Andorran system.

6.8.2. Metabolic characteristics in relation to productivity and dissipation.

Figure 10 links the economic labour productivity (ELP) and the exosomatic metabolic rate (EMR), expressed in gross energy requirement, of the countries considered at level n. At this level the characteristics of the whole society are affected both by extensive variables (size of the population, total consumption of resources) and intensive variables (overall consumption per capita). The diameter of the circles represents the energy throughput (ET) per capita in GJ per capita. Figure 10 gives an idea of the dependency on resources needed to perform the economic activity.

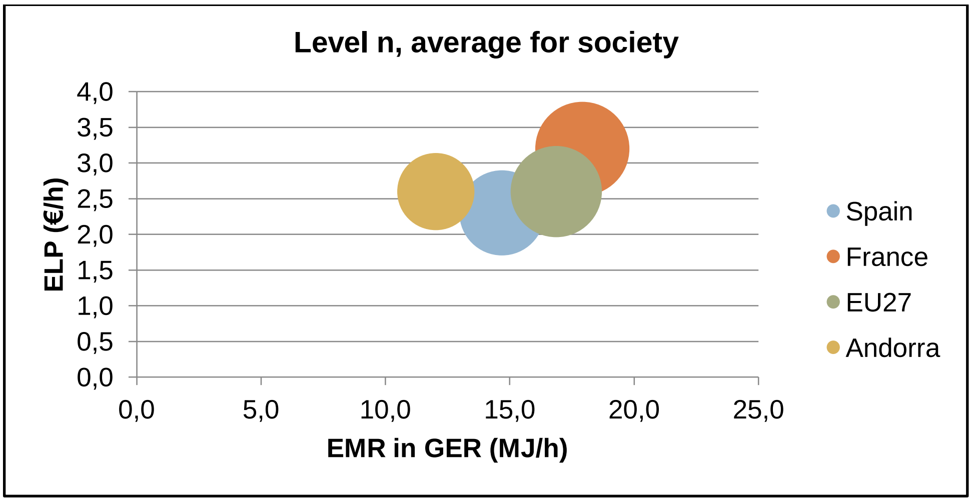


Figure 10. Exosomatic metabolic rate (EMR) and economic labour productivity of Spain, France, the EU and Andorra. Source: Elaboration on data from Velasco-Fernández (2017); CRES (2018) and Travesset-Baro (2017).

As we can see, Andorra achieves an economic performance similar to that of the EU (2,6 €/h), above that of Spain (2,3 €/h) and lower than that of France (3,2 €/h). Furthermore, Andorra's energy requirements per hour of human activity (12 MJ/h) and per capita (105 GJ) are lower than those of the surrounding countries considered (for instance, 15 MJ/h in Spain and 17 MJ/h in EU and 129 GJ p.c. in Spain and 148 GJ p.c. in EU). Something that seems logical given the inexistence of an industrial sector demanding highest energy requirements — between 200 and 1400 MJ/h in the case of high energy intense sectors and between 50-200 MJ/h in the case of medium energy intensity sectors (Giampietro et al., 2012, p.270).

Descending in the level of observation it is possible to compare the exosomatic energy metabolic rate (EMR) in the paid work (PW) and household (HH) sectors (fig. 11). The EMR in the PW sector can be considered a proxy of the technical capitalization of the sector (i.e. mechanization and computerization making the activities more competitive in the market or more effective in public services), whereas in the HH sector it is a proxy of the material standard of living (i.e. power capacity introduced to facilitate household chores and private mobility). This indicates the level of mechanization and modernization of a society, which is related to its energetic (and resource) dependency on its environment (Velasco-Fernández et al., 2020b).

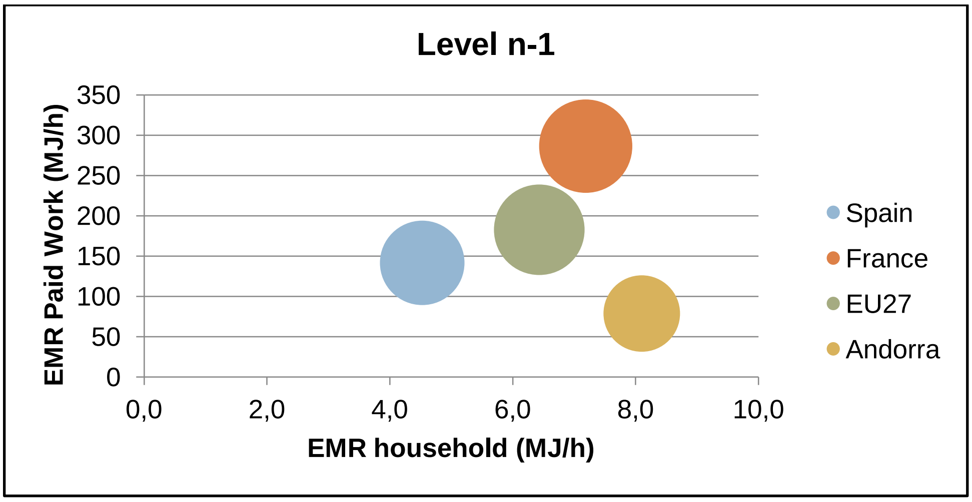


Figure 11. Exosomatic metabolic rate (EMR) in the paid work and household sectors for Spain, France, the EU and Andorra. Source: Elaboration on data from Velasco-Fernández (2017); CRES (2018) and Travesset-Baro (2017).

The PW sector in Andorra has an EMR which represents 43% of that of the EU (79 MJ/h versus 183 MJ/h). On the other hand, Andorra has a particularly high value of the EMR in the HH sector (8,1 MJ/h) that contrasts with the 6,4 MJ/h of EU, the 4,5 MJ/h of Spain and surpasses the 7,2 MJ/h of France. In this sense the value of Andorra is closer to countries like Canada (8,8 MJ/h) and USA (10 MJ/h) (values in 2008) (Chinbuah, 2010) or European countries like Finland (9,8 MJ/h) or Sweden (8,3MJ/h) (values in 2016) (Velasco-Fernández et al., 2020b). This difference could be explained by: (i) their different urbanization types, where the urban sprawl and larger houses results in more intensive use of automobiles and heating/cooling than more compact European cities, and (ii) climatic conditions. Moreover, if a high EMR in the HH sector is related to a high material standard of living —countries with low-income per capita have low ratios of EMR in the HH sector like China (2 MJ/h), Venezuela (2,1 MJ/h), Brazil (1,4 MJ/h) in the year 2000 (Eisenmenger et al., 2007) or Bulgaria (1.4 MJ/h), Romania (1.8 MJ/h), Poland (2.4 MJ/h) and Hungary (3.1 MJ/h) in 2004 (Iorgulescu and Polimeni, 2009)— the high income per capita of Andorra in relation to the EU —with a GDP per capita of 35.014 € in Andorra versus 31.020 € in the EU for the year 2015 (Departament d'Estadística, 2015)— may be a reason for the higher ratio found in Andorra. In this sense, other forms of wealth generation associated with financial operations and capital gains generated outside of biophysical processes of production of added value, which have an impact on the material standard of living, should be considered given the peculiar character of Andorra (country not belonging to the EU, with a tax differential in relation to neighboring countries and considered until 2018 a tax haven). Naredo's (2019) reflection on how the ideology of orthodox economics (considering the economic process as a self-sustaining merry-go-round between production and consumption) vanishes other ways of making money that do not fit in the production and sale of goods and services seems opportune in this case.

Finally, figure 12 relates the economic labour productivity (ELP) in the service and government sector (SG) and the corresponding exosomatic metabolic rate (EMR_{SG}) for the countries considered.

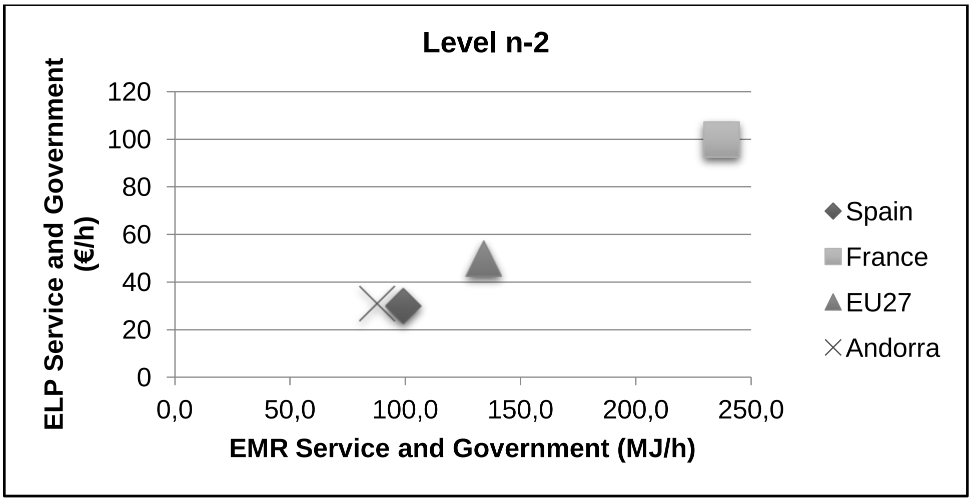


Figure 12. Exosomatic metabolic rate (EMR) and economic labour productivity in the service and goverment sector for Spain, France, the EU and Andorra. Source: Elaboration on data from Velasco-Fernández (2017); CRES (2018) and Travesset-Baro (2017).

The levels of Andorra both in relation to the monetary flow generated per hour of work in the SG sector (included in the monetary aggregate "gross value added") and in relation to the energy requirements (in gross energy requirement) per hour of work in the SG sector are close to those of Spain: 31 €/h and 87,9 MJ/h in Andorra versus 30€/h and 99,1 MJ/h in Spain. On the contrary the economic and metabolic performance of Andorra in the SG sector seems far from the values for the EU and France.

The results discussed for Andorra in this section —mainly from (Velasco-Fernández, 2017)— seem to be supported by the benchmarks established in Giampietro et al. (2012) where: (i) it is fixed a value of the ELP for the European countries between 2-4 €/h (p.48), being the value of Andorra 2,6 €/h; (ii) it is considered a value of the EMR (in GER) of 20-30 MJ/h for the average socierty (p.48), being the value of Andorra slightly below (12MJ/h); (iii) values for the EMR_{HH} are established between 2-8 MJ/h (p.264), being the value of Andorra 8,1 MJ/h; and (iv) values of the EMR_{SG} are found between 30-100 MJ/h (p.264), being 87,9 MJ/h for Andorra.

6.9. The societal metabolism of two areas of high tourism specialization: comparison between Menorca and Andorra.

In this section, the metabolic profile obtained for Andorra developed in the previous sections is compared with the metabolic characterization of Menorca based on the work of Marcos-Valls et al. (2020), both having as reference year 2015.

6.9.1 The fund elements human activity and land use.

Andorra and Menorca can be considered good examples of open metabolic systems. In fact, a large part of their human activity necessary for the maintenance of their identities comes from outside their borders. In the case of Menorca, considering is total human activity, 16% of it is composed of temporary residents. In Andorra, this percentage reaches a value of 24%. Figure 13 breakdowns the hours per capita dedicated to each functional compartment defined in this work.

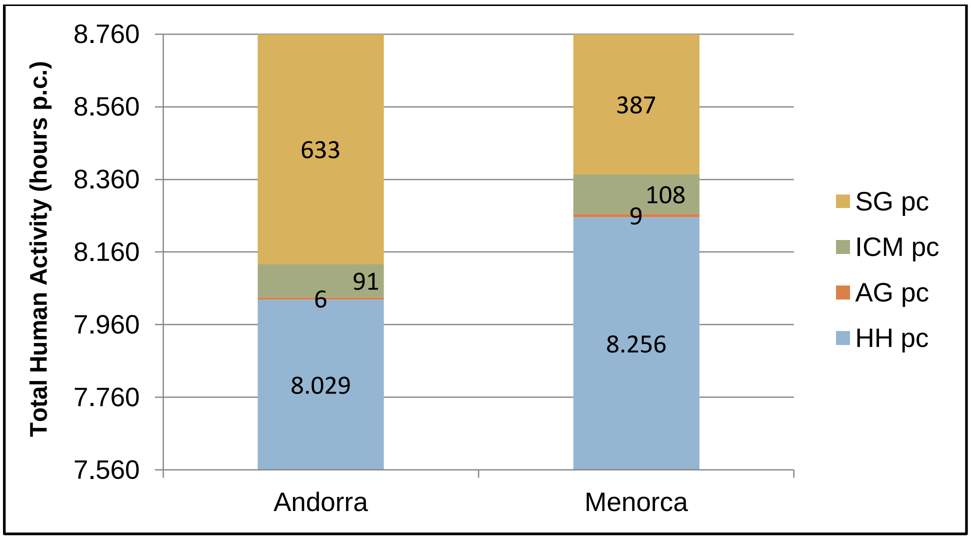
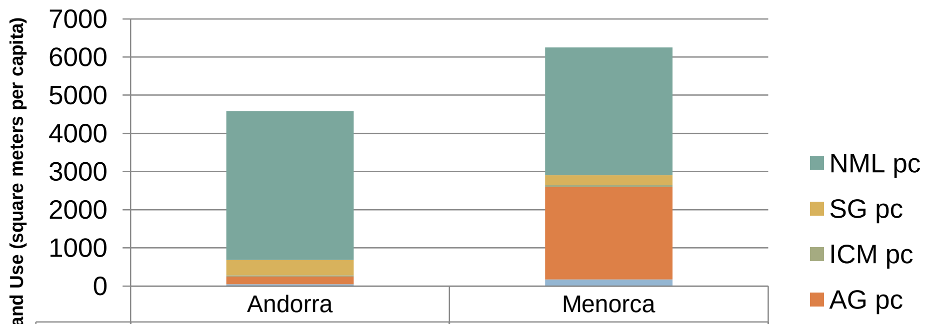


Figure 13. Hours per capita dedicated to the functional compartments considered in Andorra and Menorca. Source: Elaboration on data from Marcos-Valls et al. (2020) and CRES (2018).

Andorra shows a higher percentage of human activity devoted to the PW sector (8%) compared to Menorca (6%). Although both are economies influenced by the seasonality of tourism and the temporary pattern of residents, the lower social coverage in the principality (there is no unemployed insurance) may be a reason for this difference. Furthermore, figure 13 shows Andorra's high specialization in the service and government sector (633 hours p.c. of the 8.760 p.c. hours available versus 387 hours p.c. in the case of Menorca) and the residual character of its agricultural sector (6 hours p.c. versus 9 hours per capita in Menorca).

Figure 14, for its part, displays the distribution of the fund element land use (LU) in m^2/per capita dedicated to each functional compartment. A notable fact about Andorra is the high percentage of non-managed land (85% versus 54% in Menorca) due to the mountainous terrain that concentrates the residential and productive land uses in the center of ancient glacial valleys. In addition, the modernizing processes of the country have been accompanied by the substitution of agricultural land uses for urban land ones (CENMA-IEA, 2012b). As regards Menorca, the declaration of the island as a Biosphere Reserve has facilitated the promotion of sustainable strategies to protect the environment (UNESCO, 2018)[5]. The SG sector has the highest proportion of land use per capita among the productive sectors in Andorra (ski resorts are included in this sector). In the case of Menorca, the AG sector is the one with the larger land use per capita (2.419 m^2 p.c.).



	Andorra	Menorca
NML pc	3903	3344
SG pc	399	264
ICM pc	33	49
AG pc	202	2419
HH pc	46	173

Figure 14. Land use per capita in Andorra and Menorca. Source: Elaboration on data from Marcos-Valls et al. (2020) and CENMA-IEA (2012a).

6.9.2. Economic variables.

Figure 15 relates economic variables: the economic labour productivity (ELP in €/h), the economic land use productivity (ELUP, in €/ha) and the gross value added per capita —the size of the bubble— considering the equivalent population (€/p.c.).

Andorra has a higher productivity per hour of human activity (2,6 €/h) and per hectare of land (48.926 €/ha) than Menorca (1,6 €/h and 22.880 €/ha, respectively). In addition, the generation of added value per capita is 64% higher than Menorca (22.424 €/p.c. in Andorra and 14.300 €/p.c. in Menorca). These values are congruent with the largest percentage of hours in the PW sector in Andorra. Also with a population equivalent which amounts to 94% of Menorca and with a gross value added that in the case of Andorra is 144% higher than that of the island.

[5] Ordino, one of the seven parishes of Andorra has achieved the distinction of biosphere reserve in 2020. URL: https://en.unesco.org/biosphere/eu-na/ordino

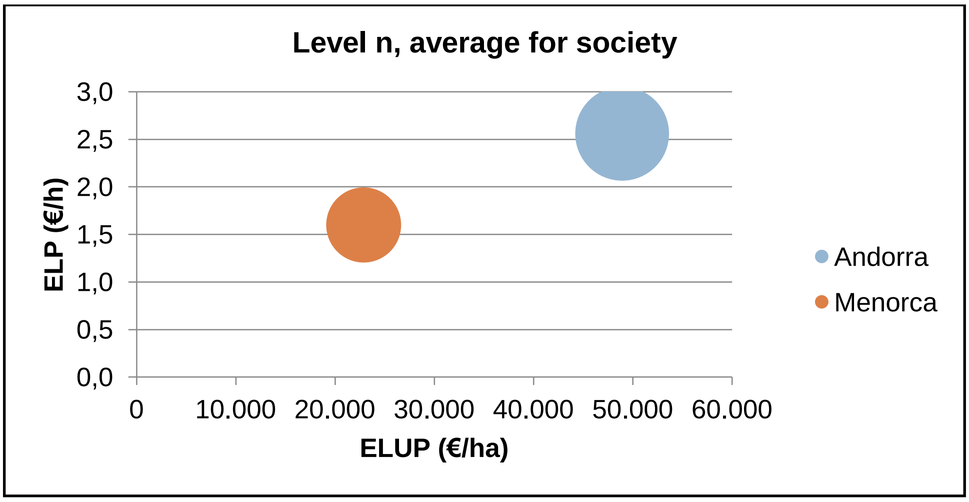


Figure 15. Economic land use productivity (ELUP) and economic labour productivity (ELP) in Andorra and Menorca. Source: Elaboration on data from Marcos-Valls et al. (2020); CENMA-IEA (2012a) and CRES (2018).

6.9.3. Energy throughput.

Regarding the energy throughput, Andorra presents a different use of energy carriers than Menorca. Figure 16 represents the total requirements (extensive variable) and the requirements per capita of the different energy carriers (electricity in thermal equivalent, heat and fuel) for the two SES considered.

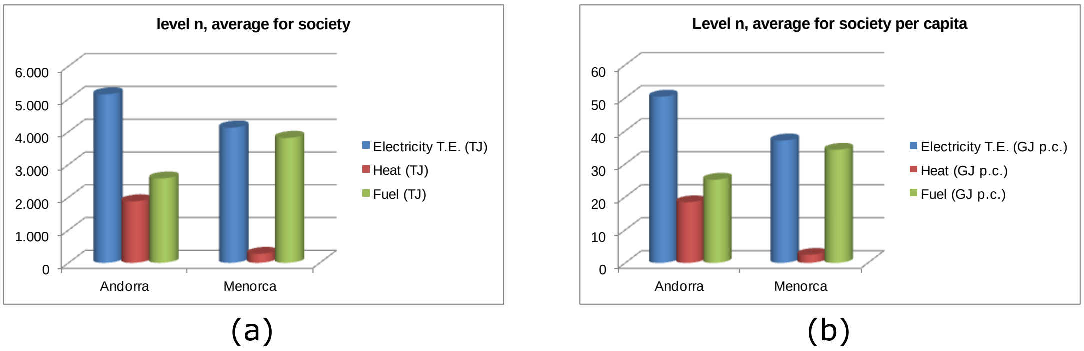
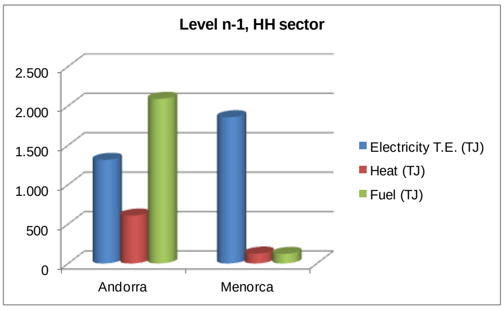


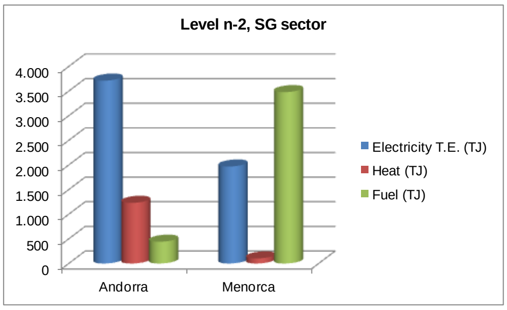
Figure 16. Energy throughput in Andorra and Menorca. Total requirements in TJ (a). Requirements per capita in GJ (b). Source: Elaboration on data from Marcos-Valls et al. (2020) and Travesset-Baro (2017).

Both systems have electricity (E) as the energy carrier with highest use, followed by fuel (F) and heat (H) in last place. Andorra presents larger consumptions of E and H (125% and 691% in reference to Menorca) and a smaller use of F. Per capita values increase these differences, becoming 136% and 753% for E and H and reducing the gap in F consumption to represent a 74% of the consumption in Menorca.

Descending in the level of observation and comparing the two most relevant functional compartments in Andorra with the respective ones in Menorca (the household sector and the service and government sector, figure 17), it is possible to observe the different pattern of consumption of energy carriers.



(a)



(b)

Figure 17. Energy carriers's consumption (Electricity, Heat and Fuel in TJ) for the household sector (a) and the service and government sector (b) in Andorra and Menorca. Source: Elaboration on data from Marcos-Valls et al. (2020) and Travesset-Baro (2017).

The bottom-up analysis made for the HH sector in Andorra (table 6) allows identifying how heating and sanitary water represent significant energy consumption in the domestic sphere (53% not counting private transport). These functions within the domestic sphere are satisfied to a large extent with the use of domestic diesel which explains the high value of the energy carrier H in Andorra. No such analysis is available for Menorca. However, the greatest use of E in the HH sector in the island appears to be related to the fact that the above functions together with the use of air conditioners (due to the benign climate of the island) are met by E. The difference in F consumption in the HH sector between the two systems is mainly due to the widespread use of private transport in Andorra. The principality only has a coach service for foreign destinations. In contrast, the high F consumption in the SG sector in Menorca is due to the inclusion of transport with the peninsula in the service sector — airline companies and naval vessels. In the absence of a more detailed analysis of the subsectors that make up the SG sector in both systems, the greater requirement of E in Andorra (almost double than in Menorca) seem to be linked to the characteristics of its main structural elements: large retails centers, financial companies, ski areas, etc.

6.9.4. Metabolic characteristics in relation to productivity and dissipation.

Figure 18 combines the exosomatic (energy) metabolic rate values (in MJ/h) of the PW and HH sector for the considered areas. The size of the bubble diameter indicates the energy throughput per capita in gross energy requirement (measured in GJ p.c.).

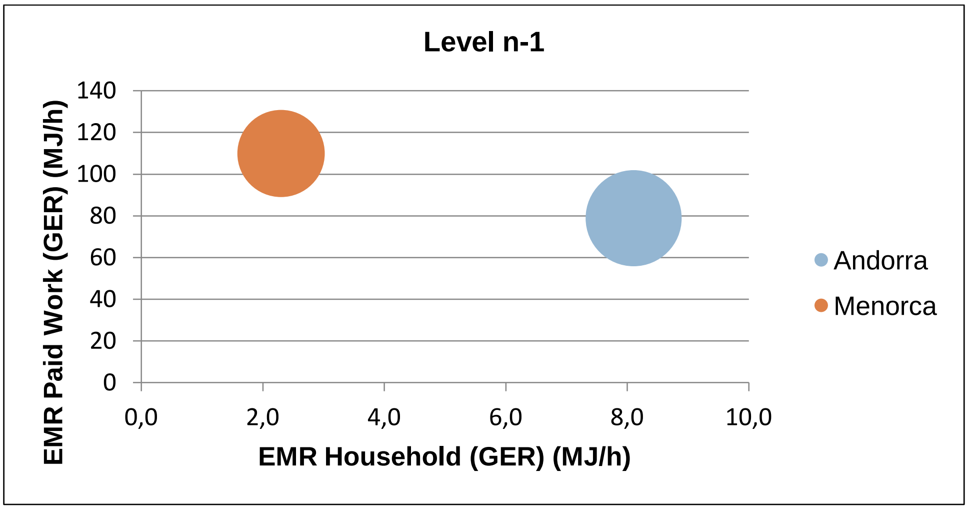


Figure 18. Exosomatic metabolic rates (EMR) in the household and paid work sectors in Andorra and Menorca. Source: Elaboration on data from Marcos-Valls et al. (2020) and Travesset-Baro (2017).

As can be seen, different values are obtained depending on the level considered. An analysis from complexity implies connecting different levels and dimensions. Andorra has greater per capita requirements than Menorca (105 GJ p.c. versus 87 GJ p.c.). However, when we looked at the PW sector Menorca reaches higher values of the EMR (110 MJ/h —Menorca— 79 MJ/h — Andorra). Although total ET requirements in the PW are quite similar (ET in Andorra in the PW is 96% of the Menorca), the lower number of hours worked in the productive sectors in Menorca (75% compared to Andorra) and the existence of sectors that are very energy intensive in the island (transport sector) seem to make a difference. Do not forget that the EMR is defined as the quantity of exosomatic energy transformed per hour of human activity. This indicator is basically driven by the use of power capacity and in that sense we use it as a proxy of the level of capitalization of the sectors: how much technical capital (machinery, devices and infrastructure in a wide sense) is used to perform a certain activity. Regarding the energy use per hour of human activity in the HH sector, data show the same results discussed in the previous section. The value of Andorra is almost four time higher than that of Menorca (8,1 MJ/h) versus 2,3 MJ/h).

Finally, figure 19 relates the economic labour productivity (in €/h), the exosomatic (energy) metabolic rate (in MJ/h of gross energy requirement) and the energy throughput (in TJ of gross energy requirement, the bubbles showing proportionally the weight of the use of resources — the bigger the bubble the higher the extensive variable) of the service and government sector (level n-2) for Andorra and Menorca.

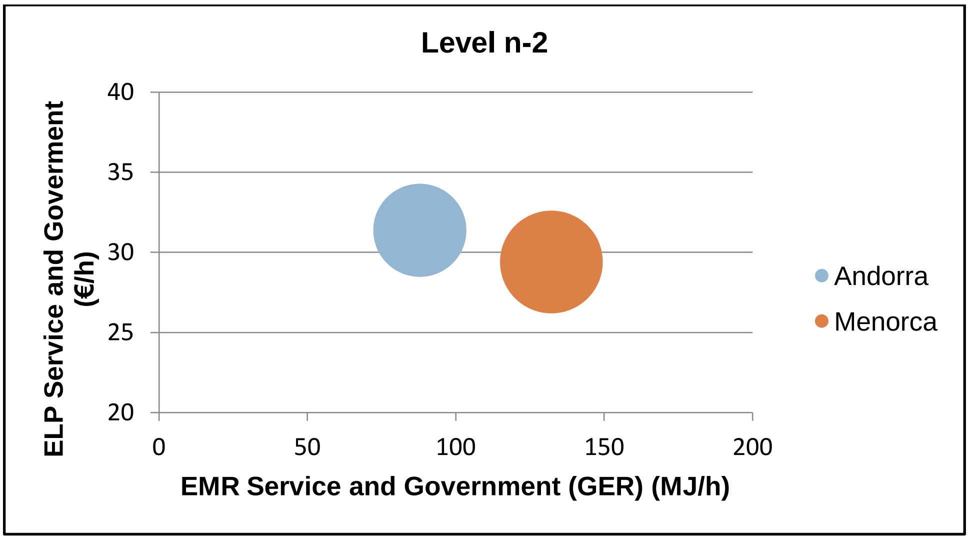
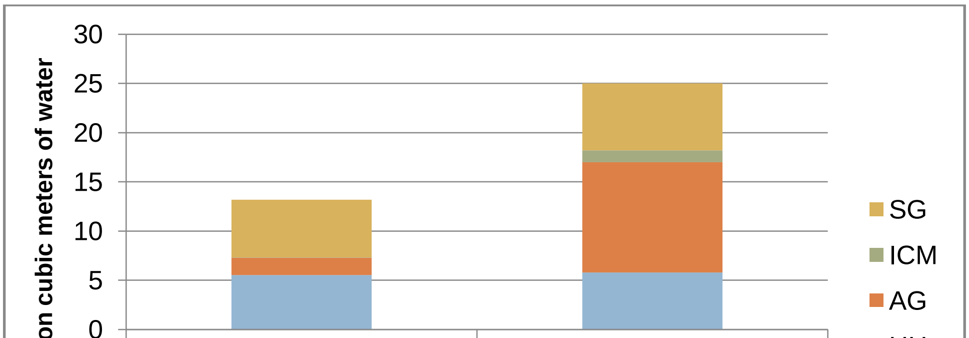


Figure 19. Exosomatic metabolic rate (EMR) and economic labour productivity (ELP) for the service and government sector in Andorra and Menorca. Source: Elaboration on data from Marcos-Valls et al. (2020) and Travesset-Baro (2017).

The generation of valued added per hour worked in the SG sector in the principality is slightly higher than that of the island (31 €/h versus 29 €/h). On the other hand, although it is true that in Andorra we find subsectors within the SG sector, such as the hotel and catering sector (see section 6.6) with high EMR (176 MJ/h in GER), as a whole the SG sector in Andorra presents a value of the EMR 34% lower than that of Menorca (88 MJ/h versus 132 MJ/h). Moreover the total requirements are 18% lower in Andorra compared to those of Menorca (5.679 TJ versus 6.884 TJ). A breakdown of the requirements and metabolic patterns of the different subsectors that make up the SG sector seems necessary for an accurate analysis. However it is not possible to obtain data at that level of disaggregation.

6.9.5. Water throughput and water metabolic rates.

Figure 20 compares water requirements (only consumptive use in mega cubic meters) of the different societal compartments considered in Andorra and Menorca. The requirements for the HH sector are similar in both areas. So are the requirements for the SG sector, which in the case of Menorca exceed those of Andorra by 5%. However, the main difference is found in the AG sector where Menorca has much greater needs (more than six times Andorra's requirements). In this sense Menorca has an important milk and cheese production system and traditional farming plays a crucial role in shaping and maintaining landscape and traditional identity. On the other hand, the modernization process developed in Andorra from the second half of the 20th century has seen the importance of the agricultural sector (under natural endowments already difficult for agricultural practice) gradually diminish towards commercial and tourist activities.



	Andorra	Menorca
SG	5,87	6,80
ICM	0,02	1,20
AG	1,74	11,20
HH	5,55	5,80

Figure 20. Water throughput (consumptive uses) for the different societal compartments in Andorra and Menorca. Source: Elaboration on data from Marcos-Valls et al. (2020) and Departament de Medi Ambient (2016b).

Water metabolic rates (in m^3/h) of the residential and service sector in Andorra and Menorca are related in figure 21. The size of the bubbles represents the consumption of water (consumptive uses) per capita (taking into account the equivalent population).

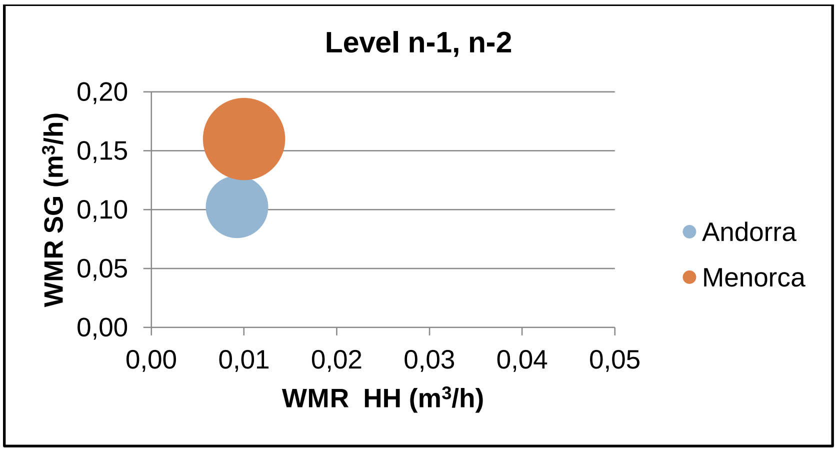
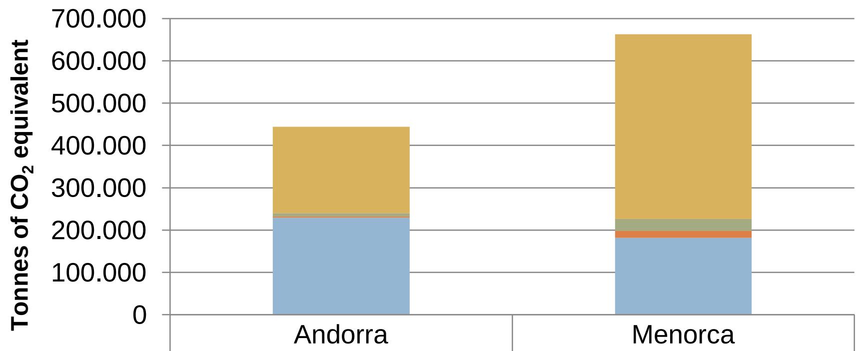


Figure 21. Water metabolic rates in the household and service and government sectors in Andorra and Menorca. Source: Elaboration on data from Marcos-Valls et al. (2020) and Departament de Medi Ambient (2016b).

We observe how both systems have the same water consumption ratio per hour in the HH sector (0,01 m^3/h). Moreover, values in the PW are 10 times higher (Andorra) and 16 time higher (Menorca) than household's values indicating that activities with high valued added are more intense water users per hour than residential activities. As expected, considering the higher total water requirements in Menorca, the per capita value in Menorca is 74% higher that the value in Andorra.

6.9.6. CO_2 emissions.

Finally, figure 22 segregates the different quantities of CO_2 emissions (in tCO_2eq) of the different societal compartments considered. We see that total emissions of Andorra represent 67% of those of Menorca. This lower environmental pressure in terms of emissions is due, in part, to the importation of electricity from France with a lower emission factor than Spain (although with other environmental problems related to the management of radioactive waste). It is important to note that in both systems, the emissions calculated do not assess the energy requirements and emissions that are externalized through imports associated with the production and transport of imported commodities which are subsequently consumed within their respective borders.



	Andorra	Menorca
SG (tCO2eq)	203.801	436.560
ICM (tCO2eq)	7.908	27.990
AG (tCO2eq)	2.576	16.750
HH (tCO2eq)	229.539	181.630

Figure 22. Emissions in Andorra and Menorca. Source: Elaboration on data from Marcos-Valls et al. (2020) and Travesset-Baro (2017).

The highest emissions in the residential sector in Andorra are due to the use of domestic fuel for heating and the massive use of private transport. On the other hand, the generalized use of electricity in the SG in Andorra and the consumption of fuel in the SG (transports) in Menorca explain the higher emissions found in the SG in Menorca.

7. Preliminary insights.

This section lists the following preliminary conclusions:

1. An integrated analysis illustrates the tension between economic productivity and environmental pressure. In this sense it is important to flag the existence of biophysical constraints affecting the option space of decision makers. Social and political factors are only a part of the dimensions to be considered. It is evident that the total number of hours available in Andorra and its initial endowment of land impose limits on its possibilities of self-organization. In particular social and institutional parameters such as ordinary legal working hours and the existence of

unemployment insurance are other key characteristics determining the productive possibilities of the country. In the same way, topography conditions do limit the allocation of land use between different societal functions. Therefore, human activity and land uses available for self-organization in relation to different tasks of the economic process concern the feasibility and viability of the metabolic pattern.

2. A characterization of the metabolic performance, metabolic rates and densities, in the use of energy, water and CO2 emissions and wastes, and the economic productivity of labor and land uses, provides a useful approach to understand how Andorra operates. However, it is important to acknowledge that the results presented so far, just show aggregated values at a very coarse scale —whole country and main economic sectors. In order to become useful for informing policy they have to be integrated with an analysis carried out at a more detailed level of analysis that can be tailored on specific research questions using the analytical concept of metabolic processors. In any case, the initial characterization presented so far has shown the possibility of the MuSIASEM framework: (i) to integrate information that is often analyzed independently; (ii) to identify how different elements of the metabolic performance of the whole are relevant when discussing about the sustainability of the system.

3. Andorra is an open system from a metabolic point of view. Its economic activities are not determined by the resources available in the physical boundaries of the country. Given its high productive specialization in the service sector (mainly tourist and financial activities), the country does not have a productive sector that can provide the goods and services necessary to maintain its identity. The HH and SG sectors (the two large functional compartments of Andorra) present a great outsourcing of resources (production of electricity, heat and fuels and waste treatment) reducing the internal environmental pressures and externalizing pressures to other SES's. On the other hand, the small side of the country reduces the risks associated with this externalization. Therefore, relying on imports reduces both the economy-environment tension and the country's sovereignty. Moreover, given the dependence of Andorra of external resources and processes, vulnerability to fluctuations in oil prices or high dependence on foreign electricity production systems translates into vulnerability to the sustainability and resilience of the metabolic pattern of the country.

4. The analysis of water gives a different picture. Water uses of the different societal compartments considered come from Andorra resources. However, a deterioration of some hydrological units is observed (Departament de Medi Ambient, 2016b) in a general framework of climate change and reduction of rainfall (Miquel et al., 2014). Besides, a different picture can be obtained if the requirements of water (virtual water) and fertile land necessary for the production of the food consumed in Andorra (endosomatic energy) are considered. This characterization is pending to be carried out within this research project in order to determine how the combination of

the metabolic rates with the analysis of openess provides an analysis where the sustainability of Andorra (in relation to energy, water and food flows) is based on shifting unsustainable and resource intensive activities elsewhere. Even looking only at this preliminary data, it is implausible that Andorra could domestically produce the current imported agricultural commodities. In addition any significant move in that direction would dramatically increase the already too high environmental pressures on local ecosystems in relation to the abstraction of water. Thus, concerns about nexus security as well as environmental burden shifting, should be taken more seriously.

5. Andorra is not only dependent on biophysical flows produced elsewhere. The country is also dependent on the fund element human activity from outside its borders (in the form of tourists and temporary workers) to maintain its identity. As explained earlier, the size of the social-economic system and its sub-sectors is assessed in terms of the fund human activity. As a result, the relative sizes of the functional and structural elements of society are directly linked to the profile of allocation of human activity (time use) across the various social practices (inside and outside the paid work sector). Thus, any human society simultaneously generates and requires human activity for its reproduction. When considering both the requirement and the supply of hours of work per capita per year per society, it becomes evident that the demographic structure and the mix of social practices in society define a forced dynamic equilibrium between supply and demand. Therefore, a shortage of human time, in one or more critical functions of the social-economic system, can constraint the trajectory of economic growth in the same way that other biophysical production factors such as water, energy and land, does. The current coronavirus health crisis can be considered as a consequence of the pressures exerted by human systems on natural ecosystems (Wallace et al., 2020). It has produced a drastic reduction in the number of tourists and one-day visitors in Andorra highlighting its vulnerability given its extreme specialization in tourism and service activities and its insertion in the global flows of people. On the other hand, Andorra, as other post-industrial societies with a low percentage of human activity in the PW sector, avoids economic stagnation through: (i) the use of technology and energy boosting labour productivity; (ii) immigration of adult workers, notably seasonal and temporary workers; and (iii) the externalization of the requirement of working time in the form of imported goods and services. Among the pending work, an assessment of the virtual hours of labour embodied in imports needs to be done. For example, in 2011 the EU used 500 hours of embodied work per capita per year in its imports that are equivalent to 120 million annual work units, i.e. virtual workers (assuming a work load per unit/virtual worker of 2,000 hours/year) (Pérez-Sánchez et al., 2020).

6. Andorra shows a productivity per hour of the labour (ELP) in line with the neighbouring countries. It has lower requirements per capita and per hour in the productive sector ($ET_{p.c.}$ and EMR_{PW}), due to the lack of an energy-

intensive industrial sector. Besides, we can conclude that the country holds a high material standard of living in the residential sector given its high EMR_{HH}. On the other hand, it is more demanding in the use of energy resources per capita (ET_{pc}) than other tourist destinations such as Menorca. However, energy use in the service and government sector per hour of work (EMR_{SG}) is less intensive than Menorca mainly due to its limited transport service infrastructure. Consequently, future projects to extend these infrastructures[6] have important implications for assessing progress towards meeting international agreements on climate and achieve a carbon-neutral economy.

7. The analysis conducted allows establishing a clear link between the maintenance of a set of dissipative structures (the constituent components) and the achievement of an economic performance determined by the metabolism of biophysical flows. Economic activities inevitably generate environmental pressures that can result into a lack of sustainability of the system. Thus, in the case of Andorra, each inhabitant needs 105 GJ of energy (in GER) per year or 129 m^3 of water per year and each euro of GVA is linked to 5 MJ of energy, 6l of water, 0,2 kgCO_2eq of emissions and 50g of waste. In the same way, the production of residential space is associated with the consumption of more than 1.031 MJ/m^2 of energy and 28 l/m^2 of water. However, under the present dominance of the narratives proposed by orthodox economics —based on the notion of economic system and the metaphor of production (Naredo, 2015)— the constant growth of the Gross Domestic Product (and population) are considered key factors, associated with the idea of progress, necessary to maintain the identity of the system (figure 23). In the same way, the processes of production of urban space (Harvey, 2019) have become an important source of capital accumulation (figure 24).

[6] https://www.diariandorra.ad/noticies/nacional/2020/11/23/l_efa_lidera_campanya_per_activar_construccio_aeroport_170417_1125.html

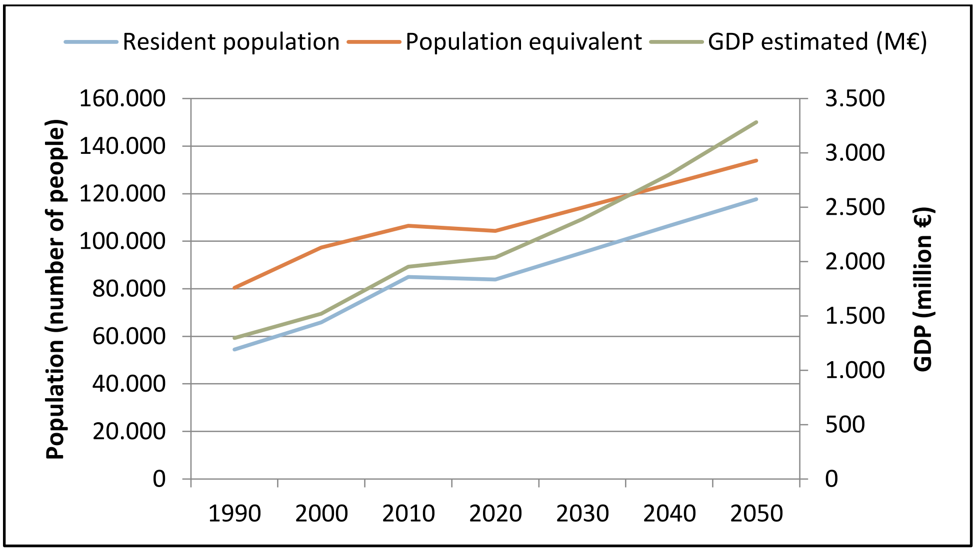


Figure 23. Population and GDP growth projections from Miquel et al. (2014).

Figure 24. Production of new urban space in Andorra. New building in a former pasture area in La Massana (a). New towers projected or under construction in Andorra la Vella (b,c,d).

In short, under the current framework of social reproduction, a more sustainable (less resource intensive) or resilient system (in which most production and transformation of resources would take place within Andorra) seems implausible. Especially when the sustainability predicament is considered to be only a technical problem (Giampietro et al., 2012) and the effects of efficiency over the metabolic performance of a society are far from being clear due to it is mixed with other effects as the Jevons paradox (Giampietro and Mayumi, 2018). For this reason, we can expect that, without a radical change in social practices, the maintenance of the current identity of Andorra will remain linked to deep biophysical dependences with other SES's tied to complex relational issues.

8. Planning until presentation of the doctoral thesis.

In the planning presented, it is considered that the pending work will be carried out during one semester full-time and two part-time semesters. Thus, the estimated completion date for the doctoral thesis is June 2022. The remaining tasks are:

1. Quantification of food flows. There is available data on food consumption, eating habits and lifestyles that will be very useful when addressing the quantitative study (Centre de Recerca Sociològica, 2018b). The characterization will be based on technical coefficients and previous works available (Cadillo-Benalcazar et al., 2020; Renner et al., 2020a).

2. Quantification of the primary energy sources for a better characterization of the environmental pressures generated. It will be possible to carry out this characterization using coefficients and available information (Di Felice et al., 2019; Giampietro et al., 2020).

3. Analysis of the openness through the construction of the four matrices: Internal End Use Matrix (EUM_{INT}), External End Use Matrix (EUM_{EXT}), Internal Environmental Pressure Matrix (EPM_{INT}) and External Environmental Pressure Matrix (EPM_{EXT}).

4. As long as technical data on Andorran ski resorts is available, a metabolic processor will be built. In this sense, the collaboration that the doctoral student maintains with the Observatori de la Sostenibilitat d'Andorra (OBSA) will be of great help in order to obtain information.

5. A check with social actors of Andorra discussing the plausibility of the findings and the robustness of the assumptions.

6. Finally, with all the integrated information it will be possible to improve the quality of the debate about the sustainability of Andorra in relation to the measurement of the energy intensity as a correct indicator of sustainability (Fiorito, 2013) and the plausibility of achieving greater energy sovereignty.

7. Writing of a third article characterizing the metabolic pattern of Andorra.

9. Expected index for the doctoral thesis.

Within the guidelines for preparing this report, a provisional index of the thesis is requested. Although in a provisional way, it is attached in appendix 4.

10. Publications

Since the beginning of the doctorate the following articles have been submitted (attached in appendix 2):

1. "MuSIASEM: una metodología para el estudio de las bases biofísicas de los sistemas socioeconómicos desde la complejidad". Communication accepted to be presented at the "Jornadas de Economía Crítica" (JEC) to be held on February 4 and 5, 2021. http://www.asociacioneconomiacritica.org/

2. The article submitted to the Ecological Economics Journal (https://www.journals.elsevier.com/ecological-economics) with title: "Limits and meaning matter: MuSIASEM as a biophysically grounded framework for analyzing the sustainability of social-economic systems".

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References

Aquae, F., 2020. Consumo de agua por persona y día en Europa [WWW Document]. URL https://www.fundacionaquae.org/europa-consumimos-una-media-128-litros-agua-persona-dia/ (accessed 22.12.20).

Ayres, R.U., Kneese, A., 1969. Production, consumption and externalities. Am. Econ. Rev. 59, 282-297.

Baccini, P., Brunner, P., 2012. The Metabolism of the Anthropocene, 2nd edition. MIT Press, Cambridge.

Cabello, V., Renner, A., Giampietro, M., 2019. Relational analysis of the resource nexus in arid land crop production. Adv. Water Resour. 130, 258-269. https://doi.org/10.1016/j.advwatres.2019.06.014

Cadillo-Benalcazar, J.J., Bukkens, S.G.F., Ripa, M., Giampietro, M., 2021. Why does the European Union produce biofuels? Examining consistency and plausibility in prevailing narratives with quantitative storytelling. Energy Res. Soc. Sci. 71. https://doi.org/10.1016/j.erss.2020.101810

Cadillo-Benalcazar, J.J., Renner, A., Giampietro, M., 2020. A multiscale integrated analysis of the factors characterizing the sustainability of food systems in Europe. J. Environ. Manage. 271, 110944. https://doi.org/10.1016/j.jenvman.2020.110944

Cañada, E., 2018. Un turismo sostenido por la precariedad laboral. Papeles Relac. Ecosociales y Cambio Glob. 140, 65–73.

Cattaneo, C., Marull, J., Tello, E., 2018. Landscape Agroecology. The Dysfunctionalities of Industrial Agriculture and the Loss of the Circular Bioeconomy in the Barcelona Region, 1956–2009. Sustainability 10, 4722. https://doi.org/doi:10.3390/su10124722

CENMA-IEA, 2012a. Mapes de cobertes del sol d'Andorra [WWW Document]. URL https://www.iea.ad/mapa-de-cobertes-del-sol-d-andorra-2012 (accessed 13.12.2020).

CENMA-IEA, 2012b. Memòria del mapa de cobertes del sòl d'Andorra (MCSA) de l'any 1972. Comparativa amb el MCSA de l'any 1995.

Centre de Recerca Sociològica, 2018a. Estudi sobre el mercat de treball d'Andorra. Institut d'Estudis Andorrans, Andorra.

Centre de Recerca Sociològica, 2018b. 2a Enquesta Nutricional d'Andorra (ENA 2017-2018). Avaluació del consum d'aliments, dels hàbits alimentaris i dels estils de vida de la població d'Andorra.

Chifari, R., Lo Piano, S., Bukkens, S.G.F., Giampietro, M., 2018. A holistic framework for the integrated assessment of urban waste management systems. Ecol. Indic. 94, 24-36. https://doi.org/10.1016/j.ecolind.2016.03.006

Chinbuah, A., 2010. International comparison of the exosomatic energy metabolic profile of developed economies. MSc. thesis,.

D'Alisa, G., Cattaneo, C., 2013. Household work and energy consumption: a degrowth perspective. Catalonia's case study. J. Clean. Prod. 38, 71-79. https://doi.org/10.1016/j. jclepro.2011.11.058.

D'Alisa, G., Di Nola, M.F., Giampietro, M., 2012. A multi-scale analysis of urban waste metabolism: density of waste disposed in Campania. J. Clean. Prod. 35, 59-70. https://doi.org/10.1016/j.wasman.2018.06.006

D'Odorico, P., Davis, K.F., Rosa, L., Carr, J.A., Chiarelli, D., Dell'Angelo, J., Gephart, J., MacDonald, G., Seekell, D.A., Suweis, S., Rulli, M.C., 2018. The global food-energy-water nexus. Rev. Geophys. 56. https://doi.org/10.1029/2017RG000591

Daly, H., 2005. Economics in a full world. Sci. Am. 293, 78-85.

Departament d'Estadística, 2019a. Superfície autoritzada [WWW Document]. URL http://www.estadistica.ad (accessed 05.04.2020)

Departament d'Estadística, 2019b. Consum d'energia elèctrica [WWW Document]. URL http://www.estadistica.ad (accessed 07.05.2020)

Departament d'Estadística, 2015. Agregats macroeconòmics [WWW Document]. URL www.estadistica.ad (accessed 08.06.2020)

Departament de Medi Ambient, 2016a. Revisió del Pla Nacional de Residus d'Andorra (2017-2020). Govern d'Andorra, Andorra.

Departament de Medi Ambient, 2016b. Estudi per a l'elaboració anyal de l'inventari i quantificació de la despesa hídrica per usos del Principat d'Andorra-Any 2015. Govern d'Andorra, Andorra.

Di Felice, L.J., Ripa, M., Giampietro, M., 2019. An alternative to market-oriented energy models: Nexus patterns across hierarchical levels. Energy Policy 431-443. https://doi.org/10.1016/j.enpol.2018.11.002

Diaz-Maurin, F., Giampietro, M., 2013. A "Grammar" for assessing the performance of power-supply systems: Comparing nuclear energy to fossil energy. Energy 49, 162-177. https://doi.org/10.1016/j.energy.2012.11.014

Diaz-Maurin, F., Kovacic, Z., 2015. The unresolved controversy over nuclear power: A new approach from complexity theory. Glob. Environ. Chang. 31, 207-216. https://doi.org/10.1016/j.gloenvcha.2015.01.014

Eisenmenger, N., Ramos-Martín, J., Schandl, H., 2007. Análisis del metabolismo energético y de materiales de Brasil , Chile y Venezuela. Rev. Iberoam. Econ. Ecológica 6, 17–39.

European Union Joint Research Center, 2010. International Reference Life Cycle Data System (ILCD) Handbook-General Guide for Life Cycle Assessment. European Union, Luxemburg.

FAO, 2019. AQUASTAT. Water withdrawal by sector [WWW Document]. URL https://www.fao.org/nr/water/aquastat/data/query/results.html. (accessed 29.03.2020)

FAO, 2013. An innovative Accounting Framework for the Food-Energy-Water Nexus [WWW Document]. URL https://www.fao.org/3/i3468e/i3468e.pdf (accessed 31.03.2021)

Fiorito, G., 2013. Can we use the energy intensity indicator to study “decoupling” in modern economies? J. Clean. Prod. 47, 465-473. https://doi.org/10.1016/j.jclepro.2012.12.031

Fischer-Kowalski, M., 1998. Society’s Metabolism: The Intellectual History of Material Flow Analysis, Part 1, 1860-1970. J. Ind. Ecol. 2, 61-78. https://doi.org/10.1162/jiec.1998.2.1.61

Fischer-Kowalski, M., Haberl, H., 2015. Social metabolism: a metric for biophysical growth and degrowth : Handbook of Ecological Economics, in: Martínez Alier, J., Muradian, R. (Eds.), Handbook of Ecological Economics. Edward Elgar Publishing, p. 512. https://doi.org/https://doi.org/10.4337/9781783471416

Fischer-Kowalski, M., Haberl, H. (eds.), 2007. Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use. Edward Elgar, Cheltenham.

Fischer-Kowalski, M., Weisz, H., 2016. The Archipelago of Social Ecology and the Island of the Vienna School, in: Social Ecology. Springer International Publishing, Cham, pp. 3-28. https://doi.org/10.1007/978-3-319-33326-7_1

Fischer-Kowalski, M., Weisz, H., 1999. Society as hybrid between material and symbolic realms. Adv. Hum. Ecol. 8, 215-251.

Funtowicz, S., Ravetz, J., 1993. Science for the post-normal age. Futures 25, 735–755.

Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process. Harvard University Press, Cambridge.

Gerber, J.F., Scheidel, A., 2018. In Search of Substantive Economics: Comparing Today’s

Two Major Socio-metabolic Approaches to the Economy – MEFA and MuSIASEM. Ecol. Econ. 144, 186-194. https://doi.org/10.1016/j.ecolecon.2017.08.012

Giampietro, M., 2019. On the Circular Bioeconomy and Decoupling: Implications for Sustainable Growth. Ecol. Econ. 162, 143-156. https://doi.org/10.1016/j.ecolecon.2019.05.001.

Giampietro, M., 2018. Perception and representation of the resource nexus at the interface between society and the natural environment. Sustainability 10, 1-17. https://doi.org/10.3390/su10072545

Giampietro, M., 2003. Multi-Scale Integrated Analysis of Agro-ecosystems. CRC Press, Boca Raton.

Giampietro, M., Aspinall, R.J., Ramos-Martín, J., Bukkens, S.G.F., 2014. Resource Accounting for Sustainability Assessment: The Nexus between Energy, Food, Water and Land use. Routledge, London.

Giampietro, M., Bukkens, S.G.F., 2015. Analogy between Sudoku and the multi-scale integrated analysis of societal metabolism. Ecol. Inform. 26, 18-28. https://doi.org/10.1016/j.ecoinf.2014.07.007

Giampietro, M., Cadillo-Benalcazar, J.J., Di Felice, L.J., Manfroni, M., Pérez-Sánchez, L., Renner, A., Ripa, M., Velasco-Fernández, R., Bukkens, S.G.F., 2020. Report on the Experience of Applications of the Nexus Structuring Space in Quantitative Storytelling. MAGIC (H2020–GA 689669) Project Deliverable 4.4, 30 August 2020

Giampietro, M., Funtowicz, S., 2020. From elite folk science to the policy legend of circular economy. Environ. Sci. Policy 109, 64-72. https://doi.org/10.1016/j.envsci.2020.04.012

Giampietro, M., Mayumi, K., 2018. Unraveling the complexity of the Jevons Paradox: The link between innovation, efficiency, and sustainability. Front. Energy Res. 6, 1–13. https://doi.org/10.3389/fenrg.2018.00026

Giampietro, M., Mayumi, K., 2009. The Biofuel Delusion: The fallacy of large scale agro-biofuels production. Earthscan Research Edition, London.

Giampietro, M., Mayumi, K., 2000. Multi-Scale Integrated Assessment of Societal Metabolism: Introducing the approach. Popul. Environ. 22, 109-153. https://doi.org/10.1023/A:1026691623300

Giampietro, M., Mayumi, K., Sorman, A.H., 2013. Energy Analysis for a Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism. Routledge, London.

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

Giampietro, M., Renner, A., 2020. The Generation of Meaning and preservation of Identity in Complex Adaptive Systems-The LIPHE4 Criteria, in: Braha, D., et al. (Ed.), Unifying Themes in Complex Systems X: Proceedings of the Tenth

International Conference on Complex Systems. Springer (Series: Springer Proceedings in Complexity), Cham, Switzerland.

Giljum, S., Lutter, S., Bruckner, M., Aparcana, S., 2013. State-of-Play of National Consumption-Based Indicators. A review an evaluation of available methods and data to calculate footprint-type (consumption-based) indicators for materials, water, land and carbon [WWW Document] Sustainable Europe Research Institute (SERI). URL https://ec.europa.eu/environment/enveco/resource_efficiency/pdf/FootRev_Report.pdf (accessed 01.04.2021).

González-López, R., Giampietro, M., 2018. Relational analysis of the oil and gas sector of Mexico: Implications for Mexico's energy reform. Energy 154, 403-414. https://doi.org/10.1016/j.energy.2018.04.134

González de Molina, M., Soto Fernández, D., G., G.C., Infante Amate, J., Aguilera Fernández, E., Vila Traver, R., García Ruiz, R., 2019. Historia de la agricultura española desde una perspectiva biofísica 1900-2010. Gobierno de España. Ministerio de Agricultura, Pesca y Alimentación, Madrid.

González de Molina, M., Toledo, V.M., 2014. The Social Metabolism. A Socio-Ecological Theory of Historical Change. Springer International Publishing, Berlin. https://doi.org/10.4324/9781315679747-14

Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V., 2016. Social Ecology. Society-Nature Relations across Time and Space. Springer International Publishing, Switzerland.

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Contributions of sociometabolic research to sustainability science. Nat. Sustain. 2, 173-184. https://doi.org/10.1038/s41893-019-0225-2

Harvey, D., 2019. La lógica geográfica del capitalismo. Icaria editorial, Barcelona.

Hoekstra, A.Y., Wiedmann, T.O., 2014. Humanity's unsustainable environmental footprint. Science 344 , 1114–1117. https://doi.org/10.1126/science.1248365.

Iglesias-Pérez, F., Blanco-González, A., Navalón, J.G.M., 2018. Informal economy and legitimacy. The Spanish case., in: Díez-De-Castro, E., Peris-Ortiz, M. (Eds.), Organizational Legitimacy. Springer, pp. 231–242.

Iorgulescu, R.I., Polimeni, J.M., 2009. A multi-scale integrated analysis of the energy use in Romania, Bulgaria, Poland and Hungary. Energy 34, 341–347. https://doi.org/10.1016/j.energy.2008.09.003

IPBES, 2019. Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystems Services [WWW Document] IPBES. URL https://ipbes.net/global-assessment-report-biodiversity-ecosystem-services (accessed 12.01.2021).

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working

Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge.

Leontief, W., 1986. Input-Output Economics, 2nd ed. Oxford University Press, New York.

Lluelles, M.J., García, E., 2018. Història econòmica d'Andorra, segles XX-XXI. Universitat d'Andorra, Sant Julià de Lòria (Andorra).

Madrid-Lopez, C., Giampietro, M., 2015. The Water Metabolism of Socio-Ecological Systems. Reflections and a Conceptual Framework. J. Ind. Ecol. 19, 853-865. https://doi.org/10.1111/jiec.12340

MAGIC Consortium, T., 2020. The Nexus Times. Megaloceros Press, Bergen.

Marcos-Valls, A., Kovacic, Z., Giampietro, M., Kallis, G., Rieradevall, J., 2020. Isolated yet open: A metabolic analysis of Menorca. Sci. Total Environ. 738, 139221. https://doi.org/10.1016/j.scitotenv.2020.139221

Martinez-Alier, J., 1987. Ecological Economics. Blackwell, Oxford/New York.

Martinez-Alier, J., Munda, G., O'Neill, J., 1998. Weak comparability of values as a foundation for Ecological Economics. Ecol. Econ. 26, 277-286.

Martinez-Alier, J., Muradian, R., 2015. Taking stock: the keystones of ecological economics, in: Martínez-Alier, J., Muradian, R. (Eds.), Handbook of Ecological Economics. Edward Elgar Publishing, Cheltenham.

Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., 2018. Special Report on Global Warming of 1.5° C.

Maturana, H.R., Varela, F.J., 1980. Autopoiesis and Cognition: The Realization of the Living. D. Reidel Publishing, Dordrecht.

Melgar-Melgar, R.E., Hall, C.A.S., 2020. Why ecological economics needs to return to its roots: The biophysical foundation of socio-economic systems. Ecol. Econ. 169, 106567. https://doi.org/10.1016/j.ecolecon.2019.106567

Miquel, C., Armengol, J.L., Dobarro, J., Rovira, N., 2014. Premier Rapport Bisannuel de l'Andorre a la Convention Cadre des Nations Unies sur les Changements Climatiques. Govern d'Andorra, Andorra.

Miquel, C., Cuyàs, M., Boneta, A., 2021. Cuarto Informe Bianual de Actualización de Andorra ante la Convención Marco de las Naciones Unidas sobre el Cambio Climático. Govern d'Andorra, Andorra.

Naredo, J.M., 2019. Taxonomía del lucro. Siglo XXI, Madrid.

Naredo, J.M., 2015. La Economía en Evolución : Historia y Perspectivas de las Categorías Básicas del Pensamiento Económico (4ed.). Siglo XXI, Madrid.

Nilsson, M., Griggs, D., Visbeck, D., 2016. Policy: Map the interactions between Sustainable Development Goals. Nature 534, 320-322. https://doi.org/10.1038/534320a

Parrique, T., Barth, J., Briens, F., Kerschner, C., Kraus-Polk, A., Koukkanen, A., Spangenberg, J.H., 2019. Decoupling Debunked: Evidence and arguments against green growth as a sole strategy for sustainability [WWW Document]. European Environmental Bureau URL https://eeb.org/library/decoupling-debunked/ (accessed 09.04.2021)

Pauliuk, S., Majeau-Bettez, G., Müller, D.B., 2015. A general system structure and accounting framework for socioeconomic metabolism. J. Ind. Ecol. 19, 728-741. https://doi.org/10.1111/jiec.12306

Pérez-Sánchez, L., Giampietro, M., Velasco-Fernández, R., Ripa, M., 2019. Characterizing the metabolic pattern of urban systems using MuSIASEM: The case of Barcelona. Energy Policy 124, 13-22. https://doi.org/10.1016/j.enpol.2018.09.028

Pérez-Sánchez, L., Velasco-Fernández, R., Giampietro, M., 2020. The international division of labor and embodied working time in trade for the US, the EU and China. Ecol. Econ. 106909. https://doi.org/10.1016/j.ecolecon.2020.106909

Prigogine, I., Nicolis, G., 1977. Self-Organization in Nonequillibrium Systems. Wiley, New York.

Renner, A., Cadillo-Benalcazar, J.J., Benini, L., Giampietro, M., 2020a. Environmental pressure of the European agricultural system: Anticipating the biophysical consequences of internalization. Ecosyst. Serv. 46, 101195. https://doi.org/10.1016/j.ecoser.2020.101195

Renner, A., Louie, H.A., Giampietro, M., 2020b. Cyborgization of Modern Social-Economic Systems: Accounting for Changes in Metabolic Identity., in: Braha, D., et al. (Ed.), Unifying Themes in Complex Systems X: Proceedings of the Tenth International Conference on Complex Systems. Springer (Series: Springer Proceedings in Complexity), Cham, Switzerland.

Reynaud, A., Pons, M., Pesado, C., 2018. Household Water Demand in Andorra: Impact of Individual Metering and Seasonality. Water 10. https://doi.org/10.3390/w10030321

Ripa, M., Di Felice, L.J., Giampietro, M., 2021. The energy metabolism of post-industrial economies. A framework to account for externalization across scales. Energy 214, 118943. https://doi.org/10.1016/j.energy.2020.118943

Røpke, I., 2004. The early history of modern ecological economics. Ecol. Econ. 50, 293-314.

Scheidel, A., Farrel, K.N., 2015. Small-scale cooperative banking and the production of capital: Reflecting on the role of institutional agreements in supporting rural livelihood in Kampot. Ecol. Econ. 119, 230-240. https://doi.org/10.1016/j.ecolecon.2015.09.008

Silva-Macher, J.C., 2016. A Metabolic Profile of Peru: An Application of Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) to the

Mining Sector’s Exosomatic Energy Flows. J. Ind. Ecol. 20, 1072-1082. https://doi.org/10.1111/jiec.12337

Smil, V., 2015. Power Density: A key understanding energy sources and uses. MIT Press, Cambridge.

Smil, V., 2008. Energy in Nature and Society: General Energetics of Complex Systems. MIT Press, Cambridge.

Steffen, W., Rockström, J., Richarson, K., Lenton, T.M., Folke, C., Liverman, D., Summerhayes, C.P., Barnosky, A.D., Cornell, S.E., Cricifix, M., Donges, J.F., Fetzer, I., Lade, S.J., Scheffer, M., Winkelmann, R., Schellnhube, H.J., 2018. Trajectories of the Earth System in the Anthropocene. PNAS 115, 8252-8259. https://doi.org/10.1073/pnas.1810141115

Tello, E., 2013. La transformació històrica del paisatge entre l'economia, l'ecologia i la història: podem posar a prova la hipòtesi de Margalef? Treballs de la Societat Catalana de Geografia 2190, 195-221.

Travesset-Baro, O., 2017. Prospectiva energètica al Principat d’Andorra. Model integrat d’avaluació de la seguretat energètica per a la transició cap a un escenari sostenibilista. Universitat Politècnica de Catalunya (PhD Thesis).

UN Enviromemnt, 2019. Global Environment Outlook (GEO-6): Summary for Policymakers. Cambridge University Press, Nairobi. https://doi.org/10.1017/9781108639217

UNESCO, 2018. United Nations Educational, Scientific and Cultural Organization. Menorca-Biosphere Reserves. [WWW Document]. URL http://www.unesco.org/new/en/natural-sciences/environment/ecological-sciences/%0Abiosphere-reserves/europe-north-america/spain/menorca/ (accessed 12.03.2020)

Velasco-Fernández, R., 2020. Depoliticizing and Repoliticizing SDGs., in: The MAGIC Consortium (Ed.), The Nexus Times. Megaloceros Press, Bergen. https://doi.org/10.24994/2020/nexustimes

Velasco-Fernández, R., 2017. The Pattern of Socio-Ecological Systems. A Focus on Energy, Human Activity, Value Added and Material Products. Universitat Autònoma de Barcelona (PhD Thesis).

Velasco-Fernández, R., Dunlop, T., Giampietro, M., 2020a. Fallacies of energy efficiency indicators: Recognizing the complexity of the metabolic pattern of the economy. Energy Policy 137. https://doi.org/10.1016/j.enpol.2019.111089

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. https://doi.org/https://doi.org/10.1016/j.energy.2018.07.122

Velasco-Fernández, R., Pérez-Sánchez, L., Chen, L., Giampietro, M., 2020b. A becoming China and the assisted maturity of the EU: Assessing the factors determining their energy metabolic patterns. Energy Strateg. Rev. 32, 1000562. https://doi.org/10.1016/j.esr.2020.100562

Velasco-Fernández, R., Ramos-Martín, J., Giampietro, M., 2015. The energy metabolism of China and India between 1971 and 2010: Studying the bifurcation. Renew. Sustain. Energy Rev. 41, 1052-1066. https://doi.org/10.1016/j.rser.2014.08.065

Wallace, Rob, Liebman, A., Chaves, L.F., Wallace, Rodrick, 2020. COVID-19 and Circuits of Capital [WWW Document]. Mon. Rev. URL https://monthlyreview.org/2020/05/01/covid-19-and-circuits-of-capital/ (accessed 5.12.20).

Williams, J., Bouzarovski, S., Swyngedouw, E., 2019. The urban resource nexus: On the politics of relationality, water–energy infrastructure and the fallacy of integration. Environ. Plan. C Polit. Sp. 37, 652-669. https://doi.org/10.1177/0263774X18803370

Appendix 1-Glossary.

Autopoietic systems: A class of systems capable of producing themselves as conceptualized by Maturana and Varela. Autopoiesis literally means "self-production" (from the Greek auto for "self" and "poiesis" for "production"). The term autopoiesis describes a fundamental complementarily between structural types and functional types found in biological and social systems. The autopoietic analysis of the living, in its original form, was initially limited to cellular life. A cell is a dissipative open system that maintains an internal structure thanks to a semi permeable spherical closed membrane that separates the cell from the medium. From these simple basis observations, Maturana and Varela arrived at a generalization of living systems based on a pattern perspective. The pattern of organization of a living system is a network of relationships in which the function of each component is to participate in the production or transformation of other components of the network. The network continually "makes itself". It is produced by its components and in turn produces those components. Thus, living systems are autopoietic systems capable of self-sustaining owing to an inner network of reactions that re-generates all system components.

Benchmark: An indicator that serves as a standard or as a point of reference by which other quantitative values may be measured or judged. In MuSIASEM a benchmark is an expected value describing one of the metabolic characteristics of a known type of socio-ecological system.

Dynamic energy budget: the central idea of the concept of dynamic energy budget in MuSIASEM is that any metabolic system has to invest energy in getting energy but at the same time it has to invest energy in expressing other behavior such as maintaining and updating social institutions in the case of human societies. The idea of dynamic energy budget implies a constraint of congruence between the characteristics of the whole and the characteristic of processes referring to an individual part. In other words, changes in one scale produces forced changes at other scales. We can associate the various functional compartments represented in the MuSIASEM taxonomy to represent a socioeconomic system as belonging to the hypercycle or dissipative part. The hypercycle part would include primary and secondary sectors, which comprise the agricultural sector, the energy and mining sector and the building and manufacturing sectors, i.e. (AG), (EM) and (BM) respectively in the acronyms used in the methodology. These sectors, although consuming energy and materials for their own operation are considered net producers of the energy carriers and materials flows (products) that are consumed by the whole society. The dissipative part, on the other hand, is composed by the service and government sector (SG) and the household sector (HH). These sectors are crucial in bearing the role of transaction activities and final consumption activities, indispensable to guarantee operation and reproduction of social institutions. The strength of the hypercycle part, defined at the level of surplus generated per unit of human activity in the hypercycle sector, determines the size of the activities that society can afford in the dissipative part. That is, there must be a balance between the energy and materials required to express the various societal functions (ensuring the fulfillment of end uses/social practices) and the supplied flow generated by the hypercycle part. If this is not the case, as in societies with a high degree of specialization in tourist activities, it is necessary to generate a monetary surplus with which to import energy and materials.

Economic labour productivity (ELP): It measures value added per hour of paid work in different functional sectors. Calculated as $ELP_i=GVA_i/HA_i$.

Economic land use productivity (ELUP): It measures value added per hectare in different functional compartments. Calculated as ELUP=GVAi/LUi.

Endosomatic energy: Different types of energy inputs, i.e. food items, to support human physiological processes.

Energy carriers: Various forms of energy inputs required by the various sectors of a society to perform their functions. Energy carriers are produced by the energy sector of a society by using primary energy sources. Energy carriers include liquid fuels, electricity and process heat.

Energy Throughput (ET): Total energy (endosomatic or exosomatic) required for the maintenance of the societal metabolism for the complete system (total) of for a given compartment (ET_i). It can be given in any of the semantic categories of accounting.

Exosomatic metabolic density (EMD): Measure of the exosomatic energy consumption per hectare of managed land (measured in Joule per hectare). It can be calculated, across different hierarchical levels, for the various compartments making-up a socio-economic system ($EMD_i=ET_i/LU_i$). It can be measured in Joule of energy carriers (then it is specific for the category of accounting, e.g. electricity, fuel, process heat) or it can be measured in Joule of gross energy requirement (primary energy equivalent).

Exosomatic metabolic rate (EMR): Measure of the exosomatic energy consumption per hour of human activity (measured in Joule per hour). It can be calculated, across different hierarchical levels, for the various compartments making-up a socio-economic system ($EMR_i=ET_i/HA_i$). It can be measured in Joule of energy carriers (then it is specific for the category of accounting, e.g. electricity, fuel, process heat) or it can be measured in Joule of gross energy requirement (primary energy equivalent).

Exosomatic energy: Different types of energy inputs (energy carriers) converted into end uses where the processes of exergy degradation take place outside the human body, but under direct human control. Exosomatic population (machines and infrastructures) imply that exosomatic energy conversions are a form of metabolism that cannot longer be related directly to individuals. Therefore exosomatic metabolism should be linked to the existence of hierarchical levels and societal compartmentalization.

Extensive variable: An additive variable that is useful to quantify the size of a system in relation to its context and a relevant observable quality. More specifically, in natural science a variable is said to be extensive if its values depend on the quantity of substance under study (e.g. volume, entropy, length, etc.)

External End-Use Matrix (EUM_{EXT}): A quantitative representation of the metabolic characteristics of the virtual supply systems associated with the production of the imports consumed by a society. The definition of these virtual systems depends on the definition of the sets of imported commodities considered and the technical characteristics of the sets of productive processes required to produce them. The matrix presents a characterization of the consumption of technosphere inputs, including both "secondary flows", such as energy, water and material, as well as "social funds", such as technology and labor, which are outside the borders of the system to produce the imported commodities. The EUM_{EXT} provides a notional representation of the metabolic pattern associated with the externalized technical processes, needed to reproduce the internal state of the system under analysis, considering the role played by imports.

External Environmental Pressure Matrix (EPM_{EXT}): A quantitative representation of the primary flows (which need primary supply and primary sink capacity provided by nature) required by technical processes taking place in virtual supply systems to produce the imports outside the borders of the system. The EPM_{EXT} is a representation of the external environmental pressures on the biosphere, needed to reproduce the internal state of a society, considering the role played by imports.

Externalization: The set of entangled social, economic and environmental effects resulting from the displacement of extractive and productive industries outside of governance boundaries (which may be regional, national or supranational). Through externalization, a social-economic system is able to reduce its requirement to secure a reliable internal flow of biophysical material, a flow that would otherwise need to be produced inside the borders of the system under analysis. Externalization plays a key role in relaxing the constraints imposed on the local combination of production processes in relation to technical viability (internal constraints determined by technical coefficients) and environmental feasibility (external constraints determined by biophysical processes outside human control).

Flow-Fund model for metabolic systems: Georgescu-Roegen proposed a flow-fund model to be used for representing the metabolism of social-economic systems. Fund elements are elements whose identity remains "the same" during the analytical representation, i.e. they reflect the choice made by the analyst when deciding "what the system is " and "what the system is made of". They are the elements in charge for carrying out the metabolism of social-economic systems transforming input flows into outflows. Examples of fund elements are capital, people and colonized land. In turn, flow elements are those elements disappearing and/or appearing over the duration of the representation. They reflect the choice made by the analyst when deciding "what the system does" or how it interacts with its context. Examples of flow elements are fossil fuels, food or wasted generated in industrial processes. MuSIASEM does not focus only on the quantification of flows, but connects funds (the agents and transformers of a process) and flows (the elements that are utilized and dissipated). The distinction between flows and funds is also useful when interfacing non-equivalent descriptive domains. So, the pace of flows used by fund elements is controlled by two types of factors: (i) external factors determined by the accessibility of an adequate input flow from the environment (e.g. provision of an adequate flow of fossil fuels thanks to the existence of natural stocks); and (ii) internal factors related with fund's capability of processing available flows during the conversion (e.g. a person can only eat a determined quantity of food per day or a machine can only convert a relative quantity of fuel into kinetic energy). Finally, it is important to note that the input derived from a stock-flow is a non-renewable resource that entails the progressive loss of the validity of the original representation of the identity of the system. Modern industrial economies are dependent of a stock-flow model (based on the exploitation of fossil fuels) from obtaining the endosomatic and exosomatic energy required to the reproduction of the social fabric. Consequently, a transition towards a more sustainable fund-flow model will have drastic consequences on the whole process of reproduction of modern industrial societies.

Functional element: A functional type is related with a large scale view. It refers to the role of a particular component which is expected to be fulfilled within a given associative context to which the component belongs. Such a role emerges from the question of why this component is necessary or why it resulted useful in the past, which translates into justifying why it is relevant to perceive and represent in the first place. The definition of a functional type defines an equivalence class of structural types which can be associated with the ability to perform the expected function.

Grammars: A set of expected relations between a given set of semantic categories and a given set of formal categories. The definition of a grammar requires a pre-analytical choice of (1) a lexicon (the categories associated with the chosen narrative), (2) a vocabulary (the list of semantic and formal categories used in the representation), (3) a list of expected relations over the various categories and (4) a set of production rules (how to calculate numbers). The use of grammars in MuSIASEM guarantees analytical clarity in the definition of the identity of the complex system under study and transparency in the election of the relevant attributes and the way numbers are produced. MuSIASEM has developed specific grammars for food, energy, water. These grammars can be considered as relational maps for the user of MuSIASEM that become accounting categories one applied to the system under study. The use of grammars allows describing the network of conversions of the flows of water, energy and food in quantitative terms. Grammars tackle the issue of scale by splitting in two the taxonomy of energy, water and food forms in relation to the external and internal view. In the external view the semantic categories used are primary sources (e.g. coal and oil for energy, fertile soil and water for food and aquifers for water). On the other hand, the internal view is focused on carriers and end uses (e.g. electricity and fuels for energy, potatoes and chicken for food and drinkable water for water). Although in practice the process of applying grammars is fairly standardized, the definition of the lexicon can be selected "à la carte" by social actors when discussing the relevance of the chosen story telling. Or, in others words, depending on the problem definition provided by the operator or the clients, it is possible to develop representations of the metabolic pattern based on different combinations of fund and flow elements.

Gross energy requirement (GER): A virtual quantity of thermal energy that is calculated using the partial substitution method to assess the total energy throughput of a society.

Gross value added (GVA): A measure of the economic value of goods and services produced in an area, industry or sector of an economy. It equals production minus intermediate consumption.

Human activity (HA): The fund element required for controlling the generation and the effective delivery of applied power generated by exosomatic devices. Human activity (a proxy of the presence of humans in the functional compartment considered), at the local scale, is measured in hours (per year) and when accounted for within the compartments belonging to the paid work sector is also referred to as human labour.

Impredicativity: In an impredicative analysis the results are both contingent and context-dependent. We can say that impredicativity is related to a dialectical process of interaction and co-evolution between the whole and the parts. For this reason, impredicativity conflicts profoundly with the simplifications inherent in reductionism and challenges the unidirectional explanation of causality. Impredicativity is a typical attribute of complex autopoietics systems. In human societies impredicativity can be easily to grasp: human reproduction depends on food production, which in turn depends on the production of technical inputs, which in turns depends on a high level of education and so on. Therefore, to characterize the dynamic equilibrium of the societal metabolism between requirements and supply of material and energy flows, at the level of the whole society as well as at the level of each of its compartments, several relevant parameters must adjust their values in a coordinated way. We can also use impredicativity to discuss future scenarios. In this way, we can relate technical coefficients or expected values, defined at a given hierarchical level (a part/subsector), with the behavior of higher hierarchical levels (the whole/sector). Or, alternatively, we can start by defining an expected (e.g. desirable) pattern of metabolism for the whole society and then look for the technical characteristics that would be required in the compartment under consideration to guarantee such pattern.

Intensive variable: A non-additive variable that is useful to quantify a relevant quality of a system, which must be expressed homogeneously over the whole system, per unit of size. More specifically, in natural science an intensive variable is independent on the quantity of material present (e.g. density, pressure, temperature, etc.)

Internal End-Use Matrix (EUM_{INT}): A quantitative representation of the metabolic characteristics of the actual "internal supply systems" (a specific set of productive processes required to produce the given supply of commodities inside the border of the system) associated with the production of the goods and services consumed by a society. The matrix presents a characterization of the consumption of technosphere inputs, both secondary flows, such as energy, water and material, and social funds, such as labor and power capacity, that are used inside the borders of the system to locally produce the goods and services consumed by the society. The EUM_{INT} provides a representation of the internal technical processes, needed to reproduce the internal state, considering only the role played by the internal supply.

Internal Environmental Pressure Matrix (EPM_{INT}): A quantitative representation of the primary flows (which require primary supply and primary sink capacity provided by nature) exchanged by technical processes with the biosphere to produce and consume goods inside the border of the system. The EPM_{INT} is a representation of the environmental pressures inside the boundaries of the system, needed to reproduce the internal state and considering only the role played by the internal supply.

Land use: Hectares of land included in one of the categories used for the accounted of managed land. It represents the social and economic functions and purposes of land.

Metabolic pattern: It refers to all energy and materials transformations that are taking place within an open social system and between this system and its environment. Under this framework, a human society and its metabolism together form an autopoietic system, a complex system that reproduces itself. The constant flow of energy and materials across the social system's boundaries and the transformation produced within their boundaries have the goal of producing and maintaining an integrated set of functional components. In turn, this hierarchically organized components have to express an expected behaviour (functions to be expressed) in order to ensure the maintenance and reproduction of the whole autopoietic social system (made of structural components). The final expression of the metabolic pattern is not about producing a flow of goods and services. This flow refers to a critical function (the provision of goods) necessary for the reproduction of the whole autopoietic system. In fact different compartments are in charge for stabilizing the critical supply of required inputs (energy, food, technology, human labour) but also with the generation of transaction activities and the realization of final consumption and other relevant activities. The final expression of the metabolic pattern is about functions to be expressed, end uses, social practices that have sense behind a certain institutional and cultural framework.

Metabolic processor: A term derived from the field of relational biology used here to refer to the relations over profiles of fund and flow elements associated with specific metabolic patterns. Metabolic processors are used to characterize the metabolic characteristics of both structural (characterized using bottom-up information) and functional (characterized using top-down information) components of the metabolic network. They have the peculiar ability to combine in a coherent pattern data that are non-reducible to each other (e.g. data from different dimensions). Metabolic processors can be interpreted as extended production functions, expressed in biophysical terms, that integrate a set of non-equivalent descriptions of the interactions that a given process has with the rest of the society (inputs and outputs exchanged within the technosphere) and with natural processes (input and output flows exchanged with the biosphere).

Mosaic effect: The mosaic effect is a tool that permits the representation of the profile of distribution of the flow and fund element over the various functional compartments defined at different hierarchical levels. The mosaic effect also shows the resulting metabolic rate (flow/fund) that characterizes requirements of different flows (e.g. food, energy, water, money) per unit of fund element. Thanks to the mosaic effect it is possible to establish a relation across hierarchical levels between the characteristics of the whole (level n) and the characteristics of the parts or sub-compartments at different sublevels. In doing so we establish a relation where the total metabolic pattern of a system is made of the aggregate metabolism of their parts. The mosaic effects implies: (1) the closure of the size of both fund elements and flow elements across the representation given at different levels. That is, congruence between the numerical values of the external referents. In this way the sum of the values of the different hierarchical levels must equal the value of the whole (level n) in relation to each one of the external referents (total amount of fund elements and total amount of flow elements). (2) The possibility of combining top-down analysis (e.g. the total energy use of a society can be derived from statistics of the energy use by the various sectors) with bottom-up analysis (e.g. the metabolic rate of each sector can be derived from technical coefficients or readings "in situ"). This makes it possible to use and double check different sources of data. The congruence of the value of the external referents between hierarchical levels does not imply a deterministic relation because of the impredicative nature of the relations in a complex system. However, it is useful in showing requirements at different levels for an informed discussion. The representation that the mosaic effect provides is useful to study internal constraints affecting the metabolic pattern across different levels. It shows the forced relation between the characteristics of the metabolic pattern of socioeconomic components across levels and allows identifying critical thresholds or bottlenecks. For example, using the mosaic effect we can represent the distribution of the fund variable "human activity" and the flow variable "consumption of energy carriers" across structural and functional levels. We also can determine the metabolic rate of each component (a flow/fund ratio that expresses what need each structural element composed of fund variables to realize its functions). A high value of a metabolic rate is correlated with structural elements with a high presence of exosomatic devices. Finally, we can detect the existence of a constraint related to the quality and quantity of energy sources at the level of the energy sector (n-4). Such constraint can be studied by checking the forced congruence between the strength of the net supply of energy carriers by the energy sector to the rest of the society and the total requirement of energy carriers by the society (assessed at level n).

The mosaic effect of modern industrial societies results in a clear decoupling between the profile of investments of human activity and investments of exosomatic energy over the various compartments of the society. Productive sectors only use a small fraction of human activity but they need huge investments of exosomatic energy. This fact can be directly linked to an increase in the level of material standard of living and to the degree of environmental loading resulting from the economic process.

Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM): A semantically open accounting framework based on the integration of conceptual insights from various disciplinary domains belonging to what has been called complexity science. It has been purposefully developed to address the sustainability predicament of social-ecological systems. MuSIASEM, (i) preserves coherence in the quantitative description of the metabolic pattern of social-ecological systems when interfacing non-equivalent descriptive domains; (ii) handles the existence of impredicativity across scales, i.e. the existence of reciprocal constraints and forced relations across hierarchical levels (the whole and the parts); and (iii) provides transparency in relation to the semantic choice of the accounting categories needed to integrate the use of non-equivalent metrics and the choice of data sources to carry out quantitative characterizations.

MuSIASEM toolkit: A set of analytical tools, based on the MuSIASEM accounting framework, used to integrate the characterization referring to various levels of analysis required to identify and study relevant attributes of societal metabolic patterns. The MuSIASEM toolkit assists in the making of three holistic checks on metabolic patterns: (i) on the external constrains in relation to the state-pressure relation; (ii) on the internal constraints in relation to the stability of the dynamic equilibrium between investments of secondary inputs in the anabolic part (household, manufacturing and service sectors) and the catabolic part (primary sectors); and (iii) on the degree of openness of the social-ecological system determined by trade. It furthermore organizes a multi-level and multi-dimensional quantitative characterization of a metabolic pattern in relation to different criteria of performance using four matrices: the internal end-use matrix, the external end-use matrix, the internal environmental pressure matrix and the external environmental pressure matrix.

Partial substitution method: This method boils down to the accounting of virtual quantities (in Joule) of primary energy source equivalent (thermal energy form such as tons of oil equivalent) per each joule of vis electrica (a form of mechanical energy): a flat conversion factor of 2,61/1 is applied to any quantity of electricity entering the system without concomitant consumption of fossil energy sources. In practical terms thus method follows the traditional accounting method used by the pioneers of energy analysis in the 1970s. In MuSIASEM the method of calculating the gross energy requirements (GER) not only considers the losses for generating electricity (2,61) but also accounts the losses for obtaining fuels (1,38) and heat (1,1). More in (Giampietro et al., 2013).

Post-normal science: It is an expression proposed by Silvio Funtowicz and Jerome Ravetz to indicate a critical situation in the production and use of science for governance. In constrast with the situation of "normal science", as defined by Kuhn, a post-normal science situation indicates that: "facts are uncertain, values in dispute, stakes high and decisions urgent". This implies changing the focus of the discussion from truth to quality by enlarging the variety of methods, criteria and actors involved in the assessment of the validity and relevance of the scientific output. Post-normal science paradigm advocates the replacement of the ambiguous concept of "scientific evidence" with more semantically-open approaches. The rigor implied in the notion of scientific evidence relies on a pre-analytical endorsement of a given framing that prevents the proverbial "thinking outside the box" further along the process. A post-normal framework, in contrast, considers different framings in relation to different concerns, hopes, scales and dimensions of analysis. This offers a way to escape the confines implied by any single framing of analysis.

Primary energy sources: Refers to the energy forms required by the energy sector to generate the supply of energy carriers used by human society. According to the laws of thermodynamics primary energy sources cannot be produced. They must be available to society, in order to make possible the production of energy carriers. Examples of primary energy sources include below ground fossil energy reserves (coal, gas, oil) blowing wind, falling water, sun and biomass.

Social Ecological System (SES): A complex of functional and structural elements combined in constituent components, operating within a prescribed boundary that is controlled and determined by the activities expressed by a given set of ecosystems (in the biosphere) and a given set of social actors and institutions (in the technosphere). In order to preserve their identity, social-ecological systems, must be capable of reproducing their multilevel organization of structural and functional elements while adapting in time. A social-ecological system is larger than the social-economic system functionally depending on it. It requires the explicit analysis of the exchanges of biophysical flows between the social-economic system and its embedding ecosystems plus the exchange of flows (through trade) with other social-ecological systems.

Structural element: A structural type is related with a local scale view. It defines the characteristics of an equivalence class of organized structures mapping on to a particular template. Realizations of these structural types are able to express a set of expected features (behaviours). Therefore, an instance of a structural type belonging to a network must be able to process a certain set of inputs and deliver a certain set of outputs at the speed expected by the rest of the network.

Sudoku effect: The way data are organized across hierarchical levels (rows) and dimensions (columns) generated three types of constraints, similar to those of the popular game, useful when analyzing current metabolic patterns or proposed scenarios. This represents the Sudoku effect in MuSIASEM: (i) vertical constraints, pointing out competition for limited resources. The endowment of production factors (fund and flow elements) in a given society is limited. If one compartment increases its share of use others compartments must rebalance their allocation; (ii) horizontal constraints, pointing out substitution of production factors. The combination of production factors must correspond to an allocation enabling each compartment (row) to perform its function; and (iii) block constraints, indicating the need of getting a dynamic energy budget (generated internally or through externalization in the supply of resources). The performance of the hypercicle and dissipative macro-components must guarantee a satisfactory performance of society as a whole.

Water Metabolic Density *(WMD):* A measure of the water consumption, per hectare of human activity, within a societal compartment. It can be calculated, across different hierarchical levels, for the various compartments making up a socio-economic system ($WMD_i=WT_i/LU_i$), in m^3/ha.

Water Metabolic Rate (WMR): A measure of the water consumption per hour of human activity within a societal compartment. It can be calculated, across different hierarchical levels, for the various compartments making up a socio-economic system ($WMR_i=WT_i/HA_i$), in m^3/h.

Water Throughput (WT): Total water required for the maintenance of the societal metabolism for the complete system (total) or for a given compartment (i). It can be given in any of the semantic categories of accounting.

Appendix 2-Works submitted for publication.

XVII Jornadas de Economía Crítica
XVII Xornadas de Economía Crítica
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XVII Jornades d'Economía Crítica

CERTIFICADO DE PRESENTACIÓN

El Comité Organizador de las XVII Jornadas de Economía Crítica certifica que la comunicación:

MUSIASEM: UNA METODOLOGÍA PARA EL ESTUDIO DE LAS BASES BIOFÍSICAS DE LOS SISTEMAS SOCIOECONÓMICOS DESDE LA COMPLEJIDAD

cuyos autores son:

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Mario Giampietro

ha sido presentada en las XVII Jornadas de Economía Crítica celebradas por vía telemática en Santiago de Compostela, los días 4 y 5 de febrero de 2021.

Y para que así conste, se expide la presente certificación, en Santiago de Compostela, a 5 de febrero de 2021

Fdo.: Xoán Ramón Doldán García
Presidente del Comité Organizador
Decano de la Facultad de Ciencias Económicas y Empresariales
Universidad de Santiago de Compostela

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Resumen de Comunicación

"MuSIASEM: una metodología para el estudio de las bases biofísicas de los sistemas socioeconómicos desde la complejidad".

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-Palabras clave: MuSIASEM, metabolismo social, análisis biofísico, complejidad.

-Clasificación JEL: Q57.

-Resumen:

Los principales retos a los que se enfrenta la humanidad en el siglo XXI, entre los que se encuentran el cambio climático, la transición hacia un sistema energético basado en renovables o la pérdida de la biodiversidad, son biofísicos. Asimismo, las iniciativas que se han articulado para dar respuesta a estas emergencias, recogidas en los Objetivos del Desarrollo Sostenible (ODS), necesitan de la integración de información procedente de diferentes dimensiones (la biofísica, la económica, la social) y escalas de análisis. La economía ecológica (EE) se estableció formalmente en 1989 con el ambicioso plan de transformar las relaciones sociedad-naturaleza orientándolas hacia la sostenibilidad, entendida ésta como el respeto por los procesos ecológicos. Coincidiendo recientemente con los 30 años del establecimiento de la disciplina, y en vista de la actual coyuntura, diversos autores han reflexionado sobre la necesidad de una vuelta a sus orígenes, emplazando la comprensión biofísica del proceso económico en el centro de la agenda de investigación. En la presente comunicación se argumenta que la metodología Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) es una excelente candidata para dar operatividad a este ambicioso plan. Para ello se expone de una manera clara y accesible las principales características del enfoque. Además, diversos conceptos teóricos que fundamentan la metodología son revisados y relacionados con pilares conceptuales de la EE como la inconmensurabilidad de valores o la sostenibilidad fuerte. Finalmente se reflexiona sobre el potencial de MuSIASEM para vislumbrar espacios de cambio que promuevan unas prácticas sociales más sostenibles.

Comunicación

1. Introducción.

La actual crisis sociosanitaria de la COVID-19 pone de relieve las profundas interdependencias entre sistemas humanos y naturales. La presión ejercida por las sociedades humanas, materializada en términos de destrucción de la complejidad de los ecosistemas regionales, de desforestación y de producción de espacios urbanos, junto con un sistema económico global hiperconectado, han sido factores claves para la emergencia de la pandemia (Wallace et al., 2020). En un sentido más amplio, conceptos como "Antropoceno", "Gran Aceleración", "Siglo de la Gran Prueba" o "Límites Planetarios" forman ya parte del imaginario colectivo e indican un deterioro ambiental incuestionable producido por las presiones humanas sobre el mundo natural (UN Environment 2019) que pone en peligro la continuidad del equilibrio planetario y la sostenibilidad de las sociedades humanas (Steffen et al., 2018).

Lejos de aceptar esta realidad, la economía ortodoxa (EO) mantiene una visión que ignora la dependencia de los sistemas socioeconómicos del macrosistema natural y la consiguiente existencia de procesos fuera de control humano que imponen límites. El objeto de la ciencia económica y la definición de riqueza social, se reduce al estudio de los bienes y servicios apropiables, valorables (en dinero), intercambiables y producibles. A su vez, la representación del proceso económico se encuentra enclaustrada en el universo autosuficiente de los valores de cambio, con la consiguiente separación entre escasez subjetiva y objetiva y entre lo económico y lo físico (Naredo 2015). En consecuencia, la perspectiva reduccionista de la EO respalda políticas que destruyen los ecosistemas y los fundamentos sobre los que se sustenta la vida (Røpke 2005).

Con el convencimiento que las herramientas propuestas por la EO son insuficientes para representar las complejas relaciones sociedad-naturaleza y tratar la crisis ambiental, la economía ecológica (EE) se estableció formalmente en 1989 con el ambicioso plan de desarrollar un nuevo paradigma económico basado en la dependencia de los sistemas sociales y económicos de una realidad biofísica que los sustenta y los limita (Daly 1977; Georgescu-Roegen 1971). Bajo un marco ontológico radicalmente diferente al de la EO, la EE propone una narrativa termodinámica del proceso económico. La perspectiva de la EE, sin caer en el reduccionismo, considera a las sociedades humanas como sistemas naturales y a los procesos económicos como procesos metabólicos que deben ser caracterizados en términos de flujos de energía y materiales. El objetivo final de la disciplina era proveer con nuevas herramientas epistemológicas para la comprensión de la escala, el uso de recursos e impactos generados por las sociedades humanas a la vez que ofrecer políticas alternativas para transformar las sociedades hacia la sostenibilidad (Røpke 2004; Spash 2015). Posteriormente la EE se ha embarcado en una fase de pluralismo metodológico y transdisciplinariedad, que le han hecho perder sus raíces heterodoxas para hacerla más compatible con la EO (Melgar-Melgar y Hall 2020; Spash 2020). Así, las aproximaciones monetarias y basadas en mecanismos de mercado han ido ganando peso con respecto a enfoques biofísicos (Plumecocq 2014).

Tras más de treinta años desde el establecimiento formal de la EE se hace cada vez más patente el carácter interrelacionado y sistémico de la crisis ambiental, que también es económica y social. Asimismo, la incapacidad de la EO, convertida en instrumento de estabilización de la actual estructura de poder, para hacerla frente apoyada en sus dos principales paradigmas: el crecimiento económico ilimitado y las valoraciones monetarias y el uso de mecanismos de mercado (Giampietro y Funtowicz 2020). En este sentido, diversos autores abogan por una vuelta de la EE a sus orígenes más heterodoxos y contestatarios, emplazando la comprensión de los sistemas socioeconómicos en términos biofísicos y el rechazo a los presupuestos de la EO, en el centro de la agenda de investigación (Daly 2019; Melgar-Melgar y Hall 2020; Pirgmaier y Steinberger 2019; Spash 2020).

En la presente comunicación se presenta a la metodología *Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism* (MuSIASEM) como una excelente candidata para dar operatividad al ambicioso plan fundacional de la EE ahora de nuevo reivindicado. En una aproximación biofísica o ecointegradora (Naredo 2015) el proceso de reproducción social debe contextualizarse siempre bajo una permanente y cambiante relación metabólica con la naturaleza (Harvey 2010). Esto se traduce en la necesidad de herramientas que aporten información relativa a la disponibilidad de recursos, generación de residuos, uso de los distintos flujos metabolizados en el interior del sistema socioeconómico, producción de presiones e impactos ambientales y el reconocimiento de incertidumbres fuertes (efecto rebote, paradoja de Jevons, dificultades epistemológicas, etc.). MuSIASEM es un enfoque innovador para el estudio de la sostenibilidad de las sociedades humanas que da respuesta a estas necesidades. Es una de las principales metodologías en el campo de la investigación sociometabólica (Haberl et al., 2019) que a su vez está relacionada con una vieja tradición en el campo de la teoría económica: el estudio substantivo (en especie, "in natura") de la economía. De acuerdo con Gerber y Scheidel (2018) MuSIASEM es una de las principales metodologías para el estudio substantivo del proceso económico de una manera sistémica.

La originalidad de MuSIASEM radica en poseer unas robustas bases teóricas basadas en la integración de diferentes ideas y conceptos de la ciencia de la complejidad (Giampietro et al., 2012, 2013; Giampietro y Renner 2020; Renner et al., 2020). Debido a su especificidad, el principal objetivo de la comunicación es presentar la metodología de manera accesible en lengua castellana a la vez que clarificar y discutir algunos de sus conceptos teóricos para facilitar su comprensión e incentivar su aplicabilidad. En este sentido la presentación se organiza como sigue: en la siguiente sección se presentan ideas básicas de la metodología en relación a su aproximación al sistema económico, al proceso económico y a la sostenibilidad. El apartado tercero revisa y discute varios conceptos teóricos habituales en la literatura sobre la metodología. Finalmente, la comunicación se cierra con algunas consideraciones finales.

2. MuSIASEM: nuevas perspectivas para los retos actuales.

Desde la perspectiva de MuSIASEM los sistemas sociales y los sistemas naturales son sistemas complejos autoorganizados y deberían ser estudiados conjuntamente como un sistema interdependiente (Giampietro 2019a). Este punto de vista reconoce que el funcionamiento de los ecosistemas es decisivo, no sólo por la provisión de recursos naturales y como sumidero de desechos, sino porque provee con una gran variedad de servicios ecológicos sin los cuales las sociedades humanas no podrían florecer (ciclo hidrológico, regulación del clima, mantenimiento de la composición atmosférica, renovación de fertilidad suelos, etc.). Además, el estado de un sistema de estas características no es observable ni controlable a través de precios y valoraciones monetarias.

El hecho de considerar a un sistema como complejo presenta indudables retos epistemológicos. Por un lado, el comportamiento del todo no es evidente del estudio de sus partes. Hay que tener en cuenta el patrón, entendido como una configuración de relaciones determinada (Capra 1996). Así, desde la perspectiva de MuSIASEM el sistema socioeconómico se entiende como una totalidad integrada que emerge de las relaciones organizadas entre sus partes. Por otro lado, la complejidad implica tener en cuenta el punto de vista del observador y la existencia de percepciones no equivalentes de lo que es relevante a la hora de representar un fenómeno (Ahl y Allen 1996). Un enfoque desde la complejidad reconoce la existencia de inconmensurabilidad social y técnica. La primera hace referencia a la existencia de diferentes actores con valores opuestos y diferentes percepciones e intereses. La segunda a la imposibilidad de resumir todas las posibles representaciones a una única dimensión o escala (Giampietro et al., 2012). Con el objetivo de obtener una caracterización lo más completa posible del sistema económico, MuSIASEM integra diferentes dimensiones (económica, biofísica, demográfica y ecológica), considera diferentes niveles de análisis (la totalidad del sistema, compartimentos y subcompartimentos) y aplica diferentes escalas temporales y espaciales (Giampietro y Mayumi 2010). Todo ello representa un punto de partida radical para el estudio del metabolismo social que contrasta con visiones reduccionistas basadas en la adopción de una única escala y una única dimensión.

Diversas ramas de la teoría de la complejidad sugieren una fuerte analogía entre los procesos autoorganizados de los sistemas ecológicos y de los sociales (Giampietro y Renner 2020; Renner et al., 2020). Ambos requieren la existencia de favorables condiciones ambientales para su desarrollo y la habilidad de poder usar los recursos disponibles (Giampietro 2019b). Así, desde la narrativa metabólica que utiliza la metodología, se concibe al sistema económico como un sistema disipativo. Este tipo de sistemas necesitan constantemente obtener inputs de su medio ambiente (energía y materiales) y poder depositar en él desechos para mantener su identidad y estructura interna (Prigogine y Nicolis 1977). Son disipativos en el sentido de que tienen estructura pero no la estabilidad de los sólidos: se disipan cuando el suministro de energía se acaba. Por consiguiente son sistemas en reacción continua capaces de compensar su ritmo de generación de entropía interna a expensas de la energía libre tomada del medio ambiente y devuelta al mismo en forma degradada.

El uso de la metodología MuSIASEM implica modificar nuestro nivel de observación en el análisis de un sistema socioeconómico. La unidad de estudio no es un sistema económico aislado y autosuficiente (o con intercambios con el exterior meramente en términos de comercio exterior) sino un sistema socio-ecológico, formado por dos elementos básicos: la tecnosfera y la biosfera. El primero incluiría un conjunto de agentes sociales, instituciones y artefactos bajo control humano (lo que vendría a ser un sistema socioeconómico desde la visión convencional) que genera la cantidad de entropía positiva necesaria para el mantenimiento de sus estructuras internas y la expresión de las funciones asociadas a la identidad del sistema. El segundo, por su parte, englobaría a un conjunto de ecosistemas que compensaría la destrucción de gradientes favorables por la estructura disipativa (Giampietro 2019a).

Partiendo del trabajo de Georgescu-Roegen (1971), MuSIASEM también nos incita a repensar el proceso económico. El economista rumano consideraba que la finalidad última del proceso económico es el disfrute de la vida y que el valor se deriva del flujo inmaterial generado por la producción (si bien materia y energía de baja entropía y trabajo humano son elementos indispensables del proceso de producción). Siguiendo esta línea de razonamiento, en MuSIASEM el sentido último del proceso económico no es la producción aumentada de bienes y servicios sino asegurar el mantenimiento y la reproducción de los componentes constituyentes (o elementos estructurales) de la sociedad, básicamente personas y unos usos del suelo determinados. Para ello se hace necesaria la existencia de un conjunto de elementos funcionales que garanticen una serie de usos finales o prácticas sociales imprescindibles para la reproducción social (por ejemplo, un sector agrícola que produzca alimentos, un sistema de transporte que nos permita la movilidad, un sector doméstico que asuma la crianza y cuidado de las personas, etc.). Por su parte, el concepto de patrón metabólico, una de las ideas clave de la metodología, haría referencia a los requerimientos de energía y materiales del conjunto de componentes funcionales. Este puede ser expresado como ratios metabólicos en términos de uso de recursos por hora de actividad humana o densidades metabólicas en términos de requerimientos de recursos para los diferentes usos del suelo (agrícola, industrial, residencial, etc.). Evidentemente, economías con diferentes configuraciones de elementos estructurales y funcionales generarán patrones metabólicos distintos.

MuSIASEM habilita un análisis de la sostenibilidad basado en una caracterización cuantitativa del patrón metabólico del sistema bajo estudio. Para ello la metodología utiliza diferentes niveles de observación: (i) una visión interna, relacionada con el concepto de "viabilidad" y asociada a procesos bajo control humano sujetos a limitaciones internas (relacionadas con la tecnología disponible y las instituciones y capacidades humanas); (ii) una visión externa relacionada con el concepto "factibilidad" y asociada a procesos fuera de control humano sujetos a limitaciones externas (por ejemplo, disponibilidad de fuentes de energía primaria o la capacidad de absorción de desechos de los ecosistemas); y (iii) una visión normativa relacionada con el concepto de "deseabilidad" asociada a la compatibilidad con valores sociales (Giampietro et al., 2014).

La visión interna estudia el modo en que los diferentes elementos funcionales de la tecnosfera metabolizan diferentes inputs (por ejemplo vectores energéticos como la electricidad o el gasoil) para realizar su cometido. Este análisis se realiza con la matriz de usos finales (Velasco-Fernández et al., 2018; Velasco-Fernández et al., 2020). La visión externa, por su parte requiere, contemplar la existencia de un adecuado aporte de inputs desde la biosfera a la tecnosfera (en términos por ejemplo de fuentes primarias de energía como el petróleo o el carbón) y la generación de desechos y emisiones desde la tecnosfera a la biosfera. La metodología dispone de la matriz de presiones ambientales y la matriz de impactos ambientales para realizar este análisis (Ripa y Giampietro 2017). Finalmente, la deseabilidad del patrón metabólico requiere una reflexión sobre la identidad de la sociedad, sus valores y creencias, que va más allá de consideraciones cuantitativas y debe ser realizado en un marco de ciencia posnormal (Funtowicz y Ravetz 1993).

En conclusión, en un mundo donde todas las partes están conectadas, reducir la presión sobre uno de los varios límites ecológicos generará nuevas presiones en otros límites. En este sentido, el estudio de la sostenibilidad presenta indudables retos. MuSIASEM permite analizar la sostenibilidad de un sistema socioeconómico integrando diferentes niveles de observación: la relación de las partes con el todo (visión interna), la relación del todo con el contexto (visión externa), expresada en términos de generación de presiones ambientales, y la relación entre identidad y contexto a medida que se interactúa y se modifica constantemente el entorno (visión normativa).

Una vez planteadas las ideas generales de la metodología, el siguiente apartado presenta y discute diferentes conceptos teóricos relevantes en la literatura sobre MuSIASEM con el objetivo final de incentivar su aplicabilidad desde la riqueza de sus fundamentos teóricos.

3. Conceptos teóricos.

3.1. *Proceso semiótico*

Las sociedades humanas mantienen una relación dialéctica con su medio ambiente y por eso deben estar permanentemente adaptándose a las nuevas condiciones que, en parte, han creado. En este sentido son sistemas anticipativos (Rosen 1985) que necesitan del uso de modelos, sobre su interacción con el medio ambiente y con otras sociedades, para aprender y adaptarse. A su vez, la producción de conocimiento científico es clave a la hora de generar modelos anticipativos que posibiliten la sostenibilidad. Sin embargo, las afirmaciones científicas han de ser validadas y el proceso de generación de conocimiento científico se encuentra insertado en un proceso más amplio de producción de sentido y construcción de realidad que define las prioridades de la sociedad en su conjunto: el proceso semiótico (Giampietro 2019b).

Desde un punto estrictamente conductivista, el comportamiento de todo organismo puede denominarse "intencionado" al tratarse de un comportamiento dirigido a un objetivo. Los sistemas vivos validan la utilidad de sus modelos a través de un proceso de interacción con el mundo exterior basado en la autoregulación desde la retroalimentación (Capra 1996). Percepciones relevantes del mundo exterior (semántica) son trasladadas a representaciones útiles (sintaxis) con las que guiar la acción (pragmática). El resultado del proceso es evaluado en referencia a los resultados previstos por el modelo. Si lo ocurrido difiere de lo esperado nuevos modelos explicativos deben ser generados hasta llegar a lo que Pattee (1995) denomina "cierre semántico" en donde todos los pasos entre semántica, sintaxis y pragmática son coherentes.

En el caso particular del las sociedades humanas obtener un "cierre semántico" es especialmente complicado, en particular en temas relacionados con la sostenibilidad en donde diferentes agentes tiene diferentes percepciones y representaciones relevantes sobre lo que es pertinente. En este sentido cuatro componentes pueden ser identificados en el proceso semiótico de las sociedades humanas: (i) el conocimiento científico aportando las representaciones; (ii) la gobernanza generando las interpretaciones; (iii) un conjunto de prácticas sociales; y (iv) un proceso político que define la identidad social y que determina las alternativas a considerar y la jerarquía de prioridades a resolver por la sociedad en su conjunto. El proceso semiótico revela el hecho de que los mecanismos de construcción de valor y significado tienen lugar a una escala que no puede atribuirse a organismos aislados. Sin embargo, debido a la existencia de asimetrías de poder en el ámbito político es importante evitar la hegemonía de determinadas perspectivas y agendas acerca de los problemas que deben ser resueltos. Además el proceso de filtraje y compresión de visiones consideradas relevantes debería ser permanentemente actualizado (Giampietro 2019b). La preocupación con respecto al cambio climático, que ha pasado de un asunto limitado a la percepción de unos pocos ecologistas hasta la consideración de un problema institucional[7], parece un buen ejemplo de identificación de nuevos problemas en el seno de la sociedad.

Las implicaciones del concepto de proceso semiótico son importantes de cara a la aplicación de MuSIASEM como herramienta cuantitativa de análisis de la sostenibilidad. Los modelos científicos son una representación simplificada de una percepción compartida de la realidad, no la realidad misma (Giampietro 2003). Hay un punto de vista del observador que debe ser integrado en el propio proceso de conocimiento. Este punto de vista se materializa en la decisión preanalítica sobre cómo observar. La selección de modelos, datos y la monitorización de resultados que resulta en hechos científicos es el resultado de la elección original acerca de qué narrativa utilizar y de qué preocupación relevante tratar. Sin embargo, la elección sobre el determinado problema que debe ser tratado no se puede justificar científicamente, más bien refleja una decisión normativa producto de un particular proceso político. Así, una definición estrecha de los problemas relevantes que deben ser tratados, que refleje sólo el interés de un grupo limitado de actores sociales, genera "hipocognición" (Lakoff 2010), esto es, un marco de análisis simplista que silencia aspectos importantes a considerar. Es por ello que el usuario de MuSIASEM debe tener presente la inevitable existencia de inconmensurabilidad de valores, una de los pilares fundamentales de la EE (Martinez-Alier et al., 1998).

Finalmente, la idea de proceso semiótico nos remite a las causas sociales profundas de, entre otras cosas, el deterioro ambiental. Las prácticas sociales son el resultado del proceso de definición de identidad y de los problemas relevantes que deben ser solucionados. En la mayoría de sociedades actuales el proceso semiótico esta hegemonizado por un conjunto de narrativas económicas producto del sistema capitalista dominante. El marco

[7] El Parlamento Europeo declaró el estado de "emergencia climática" el 28 de Noviembre de 2019.

de producción y reproducción capitalista se centra en el valor de cambio y la reproducción ampliada del capital obviando cualquier tipo de realidad biofísica (Harvey 2018; Pirgmaier y Steinberger 2019). Si bien este modelo pudo ser instrumentalmente útil en un contexto de "mundo vacío" para expandir la capacidad de captar y transformar bienes naturales en bienes y servicios útiles para las sociedades, seguir manteniendo tal marco de aspiraciones deja de tener sentido en un "mundo lleno" donde la destrucción creativa está disparando los riesgos de colapso de las sociedades (Daly 2005). Así, el problema no es sobre una entidad ontológica a la que hay que combatir (por ejemplo el cambio climático) sino sobre un sistema que promueve prácticas insostenibles como resultado de un proceso semiótico concreto y que responde a preguntas del tipo: "¿quiénes somos como sociedad?", "¿cuáles son nuestras metas?", "¿somos consumidores soberanos o seres ecodependientes e interdependientes?".

Si como sugiere Harvey en relación a su utopismo dialéctico, toda naturaleza, incluida la humana, trata de la exploración de lo novedoso (Harvey 2019), MuSIASEM debería ser usado como una herramienta para estudiar cómo la sociedad debería cambiar su identidad para hacerla compatible con su entorno, ayudando a definir un espacio para unas prácticas sociales realmente sostenibles.

3.2. *Gramáticas*

La sostenibilidad implica cambio: una variedad de sistemas humanos se adaptan e influyen sobre el medio ambiente y, en cierto punto, hacer más de lo mismo pone en riesgo su mantenimiento y reproducción (Giampietro 2003). Con la finalidad de caracterizar diferentes sistemas socioeconómicos, y poder representar su cambio, son necesarias herramientas epistemológicas flexibles que nos permitan introducir nuevas funciones y elementos estructurales. En este sentido la metodología cuenta con gramáticas las cuales facilitan una representación pertinente de las actividades metabólicas del sistema bajo estudio (Giampietro et al., 2012).

La noción más familiar del concepto de gramática está asociada con la organización estructural del lenguaje (Chomsky 1998). En el caso particular de la confección de modelos cuantitativos, el uso de gramáticas es útil para dotar de estructura operacional a la fase preanalítica. Esto implica la selección tanto de las categorías semánticas (usadas para que el análisis tenga sentido) como de las categorías formales (usadas para la cuantificación). En otras palabras, con las gramáticas podemos responder a las preguntas "¿qué es el sistema?" y "¿qué hace el sistema?" (Giampietro et al., 2012; Giampietro et al., 2014).

MuSIASEM ha desarrollado gramáticas específicas para la cuantificación de los requerimientos de energía, agua y alimentación así como para la cuantificación de la actividad humana y los usos del suelo. Estas gramáticas pueden ser consideradas como mapas relacionales que permiten describir en términos cuantitativos la red de conversiones de los flujos de energía, agua y alimentación que se producen en el seno del sistema socioeconómico una vez definida su taxonomía, es decir, los elementos funcionales y estructurales que lo componen (Giampietro et al., 2014).

Las gramáticas abordan el problema de la escala mediante una bifurcación de las categorías semánticas en relación a la visión interna y la externa. Así en la visión externa las categorías usadas son fuentes primarias (por ejemplo, carbón y petróleo para la energía, suelo fértil para la alimentación o acuíferos para la cuantificación de los requerimientos de agua). La visión interna, por su parte, es caracterizada en términos de vectores energéticos y usos finales (por ejemplo electricidad y combustibles para la energía, consumo de carne para la alimentación o agua potable para los requerimientos de agua). Con ello obtenemos una caracterización que integra tres niveles: (i) la escala local, que nos informa de cómo diferentes elementos estructurales usan los flujos biofísicos para la generación del output deseado junto con la inevitable producción de residuos; (ii) la mesoescala, que identifica el conjunto de elementos funcionales capaces de expresar un conjunto de usos finales que garantizan la reproducción del sistema; y (iii) la gran escala que analiza procesos fuera de control humano en relación a la disponibilidad de recursos y asimilación de desechos (Giampietro et al., 2014).

Si bien el proceso de aplicación de las gramáticas está estandarizado en MuSIASEM, estas pueden ser utilizadas "a la carta" por los agentes sociales. Así, dependiendo de la definición del problema, es posible desarrollar representaciones basadas en diferentes combinaciones de categorías semánticas y formales que permitan discutir la relevancia del punto de vista de un observador determinado. En este sentido, MuSIASEM ha sido utilizado para una gran variedad de análisis de sostenibilidad más allá de la caracterización del metabolismo de energía, agua y alimentación como es el estudio de la gestión de los residuos urbanos (D'Alisa et al., 2012) o el análisis integrado de los sistemas agrarios (Scheidel y Farrel 2015).

En definitiva, el uso de las gramáticas en MuSIASEM garantiza la transparencia de las decisiones tomadas tanto en la fase preanalítica como en la fase descriptiva. Las gramáticas son una herramienta flexible que facilita la definición del sistema complejo bajo estudio y la elección de los atributos relevantes a cuantificar. Además, permiten una discusión informada de la sostenibilidad gracias a que son transparentes respecto a la manera en que han sido producidos los números.

3.3. *Holon*

El término de "holon" fue propuesto por Arthur Koestler (1967) para conceptualizar el problema epistemológico consistente en el hecho de que algunas entidades consideradas como totalidades no pueden ser comprendidas sin hacer referencia al contexto con el que interactúan. Candidatos para ser etiquetados como holones incluye a células, órganos, individuos humanos y sistemas socioeconómicos. Todos ellos realizan funciones como una totalidad a la vez que intercambian energía, materiales e información con su medio ambiente. A su vez, el concepto de holon enfatiza la organización jerárquica de los sistemas vivos (Ahl y Allen 1996; Allen y Starr 1982; Giampietro 1994). Así, dependiendo de la escala adoptada para representar un sistema complejo, un elemento puede ser considerado como un todo estructural o una parte funcional de un nivel jerárquico superior. Esta doble naturaleza de los holones, explica la ambivalencia sistémica a la que un observador se enfrenta a la hora de representar elementos de sistemas complejos (Giampietro y Mayumi 2018).

El análisis relacional de Robert Rosen utiliza las cuatro causas aristotélicas para analizar un holon y determinar los elementos a observar y estudiar (Renner et al., 2020): (i) un holon debe tener una función relevante, es decir, evidenciar una causa final; (ii) su producto útil, que puede ser material o inmaterial, sólo puede ser expresado por el adecuado tipo funcional, es decir, garantizar una causa eficiente; (iii) el tipo funcional debe estar compuesto de la combinación adecuada de tipos estructurales con lo que se hace necesaria la existencia de una causa formal; y (iv) una causa material, es decir diferentes configuraciones de energía, materiales y trabajo humano, son requeridos para su existencia. El uso de esta terminología aristotélica revela el carácter complementario y no substitutivo entre recursos naturales, capital y trabajo, alineándose con la visión de la EE, e invalidando el principio de sostenibilidad débil.

Una segunda complicación epistemológica relacionada con el concepto de holon proviene de la degeneración sistémica en el mapeo de sus componentes (Giampietro y Mayumi 2018). Un tipo funcional (por ejemplo, un profesor) puede relacionarse con diferentes tipos estructurales (hombre y mujer de diferentes edades) y un mismo tipo estructural (por ejemplo, una persona) puede realizar diferentes funciones (profesora, madre y cantante de coro). Además, la identidad de un tipo (su descripción ideal) nunca coincide exactamente con su realización específica, es decir, un caso concreto de combinación de un tipo funcional con un tipo estructural (las profesoras, madres y cantantes de coro son todas especiales). Así, al representar los elementos de un sistema complejo pensamos en tipos ideales (por ejemplo la granja, la fábrica, el coche, etc.) cuando en realidad sólo podemos observar casos concretos de esas tipologías conocidas (una granja, una fábrica, un coche, etc.). En la práctica esto implica reconocer un alto grado de contingencia entre las posibles combinaciones de tipos funcionales, tipos estructurales y realizaciones concretas (Giampietro 2019b).

El concepto de holoarquía, jerarquía de holones, es útil a la hora de emplear diferentes narrativas al tratar con sistemas complejos. Dentro de una holoarquía existe una tensión entre la causalidad descendente (definición de limitaciones determinadas por la actividad de los holones de nivel superior) y la causalidad ascendente (tendencias generadas por la actividad de holones de niveles inferiores). En una holoarquía saludable esta tensión es conservada, característica conocida con el nombre de equipolencia (Iberall et al., 1980). La pérdida de equipolencia se manifiesta en el dominio de determinadas perspectivas y narrativas sobre otras perspectivas legítimas y opuestas. La sostenibilidad de los sistemas humanos nos permite pensar en estos términos. Las economías humanas se han expandido tanto como holones que están poniendo en peligro la estabilidad de los niveles superiores (sistema ecológico) de la holoarquía a la cual pertenecen. Además, el uso de narrativas económicas no es suficiente para explicar el cambio sistémico (Giampietro 1994).

Por último, el concepto de holon está relacionado con la existencia de una pluralidad de visiones y observadores. Los agentes humanos son holones y expresan simultáneamente diferentes identidades en una ecología de contextos. Los diferentes contextos son inconmensurables y no pueden compararse entre ellos o convertirse a una unidad común de medida (Bland y Bell 2007). Así, la capacidad de expresar la función prevista de una persona como padre, profesor o vegano refuerza o debilita la definición específica de sus contextos. También, las sociedades humanas son holoarquías en las que coexisten diferentes definiciones de identidad y propósito con respecto a diferentes holones de la jerarquía. Individuos, hogares, comunidades locales, gobiernos nacionales, etc., cada uno se encuentra en búsqueda de su propio "cierre semántico" dentro de su propio proceso semiótico (Giampietro 2019b).

Las ideas expuestas reverberan con fuerza en MuSIASEM. La existencia de diferentes observadores, el uso de distintas narrativas y el acoplamiento forzoso entre función y estructura son líneas de pensamiento constantes de la metodología. En términos prácticos esto se traduce en la adopción de dos visiones complementarias de análisis. Un enfoque de arriba hacia abajo que considera las relaciones funcionales entre los elementos del sistema y un enfoque de abajo hacia arriba para el estudio de los elementos estructurales que componen los diferentes compartimientos funcionales. Esta doble caracterización permite combinar evaluaciones multidimensionales procedentes de datos estadísticos con evaluaciones basadas en coeficientes técnicos observados al nivel local, garantizando la robustez del análisis.

3.4. *Autopoiesis*

Autopoiesis, del griego, significa "creación de sí mismo". De acuerdo con Luisi (2003) el estudio de la organización autopoiética de los sistemas vivos, en su forma original, se limitó a la vida celular. Una célula es un sistema disipativo que mantiene su estructura interna gracias a una membrana esférica semipermeable que separa a la célula de su contexto. A partir de esta observación, Maturana y Varela (1980) identificaron la organización circular como la organización básica de todos los organismos vivos. Así, un sistema vivo es un sistema autopoiético en donde la función de cada componente es ayudar a producir y transformar a otros componentes manteniendo al mismo tiempo la circularidad global de la red (Capra 1996).

Junto con la expresión del patrón básico de organización de lo vivo, el concepto de autopoiesis está también relacionado con el fenómeno de la percepción. Un organismo vivo reconoce y utiliza el medio ambiente en un proceso en el que no hay separación entre el acto cognitivo y la estructura interna del mismo (Luisi 2003). En otras palabras, la percepción no puede ser considerada como una representación de una realidad externa sino que se especifica a través del proceso de cognición (Capra 1996). Los sistemas vivos poseen mecanismos que les posibilitan la obtención de información del exterior y la generación de significado válido para guiar su acción. Obtienen del mundo exterior los elementos que les permiten construir su identidad lo que posibilita su aprendizaje, desarrollo y adaptación. En este sentido, la evolución es vista como el resultado del mantenimiento y adaptación de la estructura interna del organismo autopoiético en respuesta a cambios en las condiciones de su entorno (Giampietro 2019b).

Finalmente la idea de autopoiesis también se vincula a la aparición de nuevos significados asociados a la aparición de nuevas funciones observables en un nivel diferente de análisis. Propiedades emergentes son aquellas nuevas propiedades que surgen cuando un conjunto de componentes se ensamblan generando una estructura de mayor complejidad. Así, por ejemplo, la vida de una célula es una propiedad global que no puede ser atribuida a un solo componente. Lo local y lo global se correlacionan de un modo dialéctico que enfatiza la múltiple causalidad y contrasta con una visión mecanicista de la vida (Luisi 2003).

El concepto de autopoiesis es relevante en MuSIASEM. Desde la metodología las sociedades humanas son consideradas un caso especial de sistemas autopoiéticos en los cuales la definición de identidad se produce mediante un proceso semiótico que garantiza su mantenimiento, reproducción y adaptación. También, al igual que otros sistemas vivos, son sistemas disipativos alejados del equilibrio térmico con lo que necesitan un constante aporte de energía y materiales para el mantenimiento de su organización interna. Así, dependiendo del nivel de observación considerado podemos hacer una distinción entre: (i) el sistema autopoiético en su totalidad formado por el conjunto de elementos constituyentes que deben ser mantenidos (los elementos fondo del sistema); (ii) holones funcionales del nivel jerárquico inmediatamente inferior, cuya ensamblaje determina la propiedad emergente global, es decir, la existencia de la sociedad como un todo; y (iii) holones de niveles jerárquicos inferiores necesarios para el correcto desempeño de las diferentes funciones.

La actualización del proceso autopoiético, es decir, la constante reconfiguración y evolución de la identidad del sistema, es analizada bajo la emergencia de nuevos holones. El hecho de que la misma función pueda ser realizada por diferentes tipos estructurales, de que un tipo estructural pueda realizar diferentes funciones y de que la realización específica de un holon no sea exactamente predecible a partir de sus tipos ideales, permite a un sistema complejo un cambio no determinista en respuesta a requisitos internos o externos. Cuando un holon es introducido para cumplir una nueva función hablamos de innovación por emergencia. Por contra, cuando nuevos tipos estructurales son desarrollados para expresar mejor una función establecida nos referimos a innovación por diseño (Giampietro y Mayumi 2018). Un ejemplo de innovación por emergencia sería la nueva función de movilidad asociada a la electricidad con la implantación del vehículo eléctrico. Este tipo de innovaciones están asociadas a cambios en las condiciones marco (por ejemplo el cambio climático) o cambios en las expectativas del sistema (por ejemplo la necesidad de reducir las emisiones de la economía). La innovación por diseño se relaciona con situaciones de estabilidad. Un nuevo modelo de vehículo que nos permita conducir más kilómetros y de una manera más confortable sería un ejemplo de este tipo de innovaciones basadas en "hacer mejor lo mismo".

En definitiva, el concepto de autopoiesis dirige nuestra atención a los requerimientos para el mantenimiento de las sociedades humanas pero también a su carácter cambiante y adaptativo. En lo que respecta a una caracterización cuantitativa de sistemas complejos esto es especialmente relevante. La validez del análisis se limita al mantenimiento de la identidad del sistema. Sin embargo, la constante reconfiguración de los componentes de un sistema autopoiético hace explícita la limitada vigencia de una representación cuantitativa. Por esta razón el conjunto de relaciones numéricas generadas en MuSIASEM no se dirigen a la obtención de soluciones óptimas (como sucede con los modelos convencionales basados en premisas "*ceteris paribus*"), sino a la representación de un espacio de información para llevar a cabo evaluaciones contingentes (del tipo "y si...") que permiten evaluar las limitaciones o incongruencias de ciertas propuestas.

3.5. *Modelo Flujo-Fondo*

El modelo flujo-fondo es un pilar fundamental de la metodología. Desarrollado por Georgescu-Roegen (1971), cuyo trabajo fue seminal para el establecimiento de la EE como disciplina académica, el modelo flujo-fondo permite dotar de operatividad al análisis del metabolismo social desde MuSIASEM.

El término "fondo" hace referencia a los agentes que transforman flujos de entrada en un producto resultante mientras mantienen y preservan su identidad durante la duración del análisis. Los elementos fondo son los encargados de realizar las transformaciones metabólicas en los sistemas sociales. Ejemplos de elementos fondo son las personas, el capital fijo y la tierra. Por su parte los elementos "flujo" son aquellos utilizados por los elementos fondo para la realización de su función. Estos aparecen o desaparecen durante la duración de la representación. Ejemplos de elementos flujo son los combustibles fósiles, la comida o las emisiones generadas por procesos industriales. El estudio del metabolismo social utilizando un modelo flujo-fondo no se centra exclusivamente en la cuantificación de los flujos sino que conecta fondos (los agentes transformadores en diferentes procesos) con flujos (los elementos utilizados y disipados). Esto permite generar indicadores multinivel caracterizando rasgos específicos del sistema (Giampietro et al., 2012).

El uso de elementos fondo y flujo ayuda a la configuración de la definición preanalítica de la identidad del sistema a estudiar. Así, los diferentes elementos fondo distribuidos en diferentes compartimentos funcionales jerárquicamente organizados responden a la pregunta "¿qué es el sistema y qué debe ser mantenido?". Estos agentes son los elementos constituyentes del sistema y deben ser preservados y reproducidos para mantener la identidad del mismo. Además, estos elementos requieren de flujos para expresar el conjunto de funciones que permiten la reproducción social, respondiendo a la pregunta "¿qué hace el sistema?". A este respecto, las gramáticas establecidas por la metodología permiten la distribución y cuantificación de los diferentes elementos fondo y flujo.

La idea de que un nivel de organización jerárquico mayor que el individuo debería ser considerado a la hora de describir los flujos de energía en las sociedades modernas, es algo que transmite la distinción entre fondos y flujos. En este sentido es útil distinguir entre energía endosomática y exosomática. La primera hace referencia a la energía contenida en los alimentos y que es necesaria para el mantenimiento de los procesos fisiológicos humanos. La segunda, en cambio, indica la energía que es utilizada fuera del cuerpo con el objetivo de amplificar el producto del trabajo humano y el control sobre su entorno. El uso generalizado de diferentes artefactos en la tecnosfera (tecnología e infraestructuras) tiene como efecto que una gran parte de conversiones de energía en el metabolismo de las sociedades corresponda a transformaciones exosomáticas, vinculadas a niveles jerárquicos de compartimentación social superiores al individual.

Finalmente es importante distinguir entre flujos cuyo origen es un stock de aquellos originados por un fondo. Esta distinción tiene importantes implicaciones para la sostenibilidad de los sistemas humanos. El uso de un fondo conlleva una limitación determinada por la estructura física del fondo. Así por ejemplo una vaca, un elemento fondo, requiere de un tiempo para producir un litro de leche y no es posible obtenerlo en menos tiempo. Esto implica la existencia de una relación entre el elemento fondo y el ritmo al que puede proveer el flujo correspondiente. Además los elementos fondo deben ser periódicamente renovados lo que genera unos gastos adicionales para su mantenimiento. Sin embargo, en la medida en que el elemento fondo es reproducido en el tiempo, el flujo resultante de su utilización puede considerarse renovable. Por el contrario un stock, en principio, puede utilizarse a voluntad para la generación de un flujo pero el insumo que se deriva de ese stock no es renovable. Las economías modernas dependen, básicamente, de flujos originados por stocks (basados en la explotación de reservas de combustibles fósiles) para obtener los requerimientos de energía ensodomática y exosomática necesarios para la estabilidad del proceso de reproducción social. En consecuencia, una transición hacia un modelo más sostenible, como puede ser el uso de energías renovables bajo un marco fondo-flujo, implicará cambios radicales en el proceso de autopoiesis de los sistemas socioeconómicos.

3.6. *Presupuesto Energético Dinámico*

Herbert Spencer, uno de los padres fundadores de la sociología moderna, relacionaba el progreso social con el excedente de energía (McKinnon 2010). Este último posibilitaba la diferenciación social y la viabilidad de actividades culturales más allá de las relacionadas con la satisfacción de las necesidades vitales básicas. Otros eminentes investigadores como Zipf (1941, 1949), Lotka (1922) y White (1943) han desarrollado esta idea desde diferentes disciplinas. El concepto de presupuesto energético dinámico en MuSIASEM reflexiona sobre el hecho de que un sistema socioeconómico debe simultáneamente invertir energía en generar energía a la vez que destinarla para la expresión de otras funciones como el mantenimiento y actualización de diversas instituciones sociales.

El concepto de presupuesto energético dinámico para el estudio de los sistemas socioeconómicos está basado en el trabajo previo realizado para la caracterización de los sistemas ecológicos. Así, en el análisis de las estructuras de los ecosistemas, Ulanowicz (1986) diferenció, dentro de la red de flujos de materia y energía que constituyen un ecosistema, dos estructuras funcionales básicas: el hiperciclo y la parte disipativa. La primera debe proveer con un necesario excedente de energía (después de descontar el consumo propio) al resto del sistema. La segunda expresa actividades esenciales pero que degradan energía.

Siguiendo esta distinción conceptual, es posible asociar los diferentes compartimientos funcionales del sistema socioeconómico como pertenecientes al hiperciclo o a la parte disipativa. El hiperciclo (también denominado parte catabólica) comprende los procesos que tienen lugar en los sectores primarios, es decir, los sectores agrícola, pesquero, forestal, minero y energético. Estos sectores, aún consumiendo materiales y energía para estar operativos, garantizan el suministro para el consumo en otros compartimientos sociales. La parte catabólica utiliza fuentes primarias (petróleo, gas, tierra fértil, etc.) que son transformadas en inputs primarios (vectores energéticos, alimentos, etc.) para su uso por el resto de sectores económicos. Por el contrario, la parte disipativa (también denominada parte anabólica) corresponde a los procesos que tiene lugar en los restantes sectores de la economía en donde los inputs primarios son usados para generar flujos secundarios (sector industrial) o para actividades de transacción y gobierno (sector servicios y administraciones) y consumo final (sector doméstico) indispensables para garantizar la reproducción social. La fuerza del hiperciclo, definida como el nivel de excedente generado por unidad de trabajo humano, determina el tamaño y complejidad de las actividades que la sociedad puede mantener en la parte disipativa (Giampietro et al., 2012; Giampietro 2019a). En esencia esto supone que debe haber un equilibrio entre los requerimientos biofísicos necesario para expresar las diferentes funciones sociales y el flujo que es generado por los compartimientos pertenecientes al hiperciclo. En caso contrario, como sucede por ejemplo en sociedades con un alto grado de especialización en el sector servicios, un excedente monetario debe ser generado para importar energía y materiales.

El balance interno entre el hiperciclo y la parte disipativa es útil para comprender la complejidad de los sistemas sociales. La complejidad en las sociedades humanas puede ser definida como la habilidad de generar y mantener una diferenciación tanto en estructura como en comportamiento (Tainter 1988). Los componentes de la complejidad incluyen poblaciones crecientes, mayores habilidades técnicas, diferenciación y especialización social y la creciente producción de flujos de información. Así, la complejidad está asociada a un aumento de las funciones relacionadas con la parte disipativa. Como apunta Tainter (2006) la complejidad es clave para la sostenibilidad de las sociedades humanas actuando como un mecanismo para la resolución de problemas. Sin embargo el coste de la misma se materializa en la energía, trabajo, dinero y tiempo necesarios para mantener un sistema que crece para tener más partes, especialistas, regulación e información. En otras palabras, la complejidad requiere un mayor consumo de recursos y en paralelo una mayor fuerza del hiperciclo para procesarlos.

En las sociedades industriales la complejidad se mantiene gracias al uso mayoritario de energías fósiles. Esta estrategia externaliza los costes de la misma hacia el medio ambiente y las generaciones futuras. Por consiguiente, conectar los costes y beneficios de la complejidad es también considerar una visión del proceso económico desde una perspectiva biofísica.

3.7. *Análisis Impredicativo*

La impredicatividad está relacionada con el proceso de interacción y coevolución entre las partes y el todo. Una definición impredicativa es autorreferencial y dependiente del contexto. En las sociedades humanas la impredicatividad es fácil de entender: la reproducción de la sociedad depende de la producción de alimentos, que a su vez depende de competencias técnicas, que están relacionadas con un determinado nivel de educación que depende de otras funciones sociales y así sucesivamente. La impredicatividad entra en conflicto con las simplificaciones inherentes del reduccionismo y cuestiona las explicaciones unidireccionales de causalidad (Giampietro et al., 2012). Rosen (2000) considera la impredicatividad como una de los atributos de los sistemas autopoiéticos.

En MuSIASEM el análisis impredicativo (ILA), de *Impredicative Loop Analysis* en inglés, se utiliza para analizar las mutuas restricciones que se producen entre el todo y las partes de un sistema complejo. En este sentido, garantizar el equilibrio dinámico del metabolismo social de un sistema socioeconómico supone que diferentes parámetros, pertenecientes a diferentes niveles jerárquicos, deben ajustarse de un modo coordinado. El análisis impredicativo relaciona coeficientes técnicos o valores esperados definidos a un nivel jerárquico con el comportamiento de otros niveles diferentes. Así por ejemplo, podemos empezar con la definición de cuáles son las limitaciones externas a la que está sujeto el sistema (por ejemplo la tierra cultivable) y una determinación de los coeficientes técnicos (rendimientos por hora y hectárea) para calcular la cantidad de alimentos viables que pueden ser producidos o el nivel de suficiencia del sistema sin recurrir a externalizaciones (importar es una solución efectiva tanto para superar limitaciones externas como internas). O por el contrario, podemos empezar por fijar un determinado nivel material de vida para el conjunto de la sociedad y determinar los requerimientos técnicos y de actividad humana de un compartimiento determinado que serían necesarios para garantizar el cumplimiento de ese estándar.

Es importante destacar que el ILA no genera un resultado determinista. Cambios en las características de los niveles inferiores no necesariamente conducirán a cambios lineales en las características del conjunto del sistema. Cualquier combinación de cambios que se encuentre dentro del espacio de factibilidad, viabilidad y deseabilidad es admisible. La deseabilidad de una situación, esto es, una evaluación sujeta a preferencias humanas, es tan importante como la viabilidad técnica o la disponibilidad de recursos naturales para determinar la estabilidad de un determinado patrón metabólico. Sin embargo el ILA nos permite indagar en las respuestas a las preguntas sobre la sostenibilidad de un sistema humano del tipo: ¿cuánto cambiarán los requerimientos de energía y trabajo si aumenta la población o la calidad de la dieta? o ¿qué pasa en una sociedad en la que se incrementa la tasa de dependencia? Adoptar un enfoque multiescalar permite establecer vínculos entre limitaciones biofísicas (externas o internas) y su relación con diferentes niveles de observación (el todo y las partes).

El análisis impredicativo implica relacionar parámetros de diferentes escalas temporales y espaciales. Hay parámetros, por ejemplo los coeficientes técnicos, que se refieren a escalas temporales y espaciales muy específicas, como puede ser el caso del rendimiento de una determinada explotación agrícola. Otros parámetros, como la tasa de dependencia, reflejan procesos demográficos de escalas temporales diferentes. Finalmente, hay otras variables, como lo que es considerado aceptable o ético, que reflejan procesos relacionados con la identidad cultural de la sociedad (Giampietro y Mayumi 2000).

En conclusión, el ILA nos permite analizar escenarios que no son factibles desde un punto de vista biofísico, identificando factores críticos y conexiones entre valores numéricos pertenecientes a diferentes niveles jerárquicos que hacen posible el mantenimiento de un determinado patrón metabólico.

3.8. *Efecto Mosaico*

El efecto mosaico es un concepto que nos permite representar la distribución de los elementos fondo y flujo entre los diferentes compartimientos funcionales definidos a diferentes niveles jerárquicos. También nos muestra los resultantes ratios metabólicos que caracterizan los requerimientos de los diferentes flujos por unidad de fondo.

Gracias al efecto mosaico, y en la misma línea que el ILA, es posible establecer una relación entre diferentes niveles jerárquicos y mostrar la congruencia entre las características del conjunto del sistema, al nivel n, y las características de compartimentos situados en niveles inferiores (n-1, n-2, n-3, etc.). Así, se establece una relación donde el patrón metabólico resultante del sistema socioeconómico está constituido por la agregación de sus partes. Esto implica el cierre numérico del valor de las categorías formales usadas para la cuantificación de los elementos flujo y fondo. En este sentido, el valor de la suma de los requerimientos biofísicos de los diferentes niveles jerárquicos considerados debe ser igual al valor del conjunto del sistema expresado en el nivel n. Así, el efecto mosaico es útil a la hora de mostrar requerimientos a diferentes niveles en una discusión informada.

El efecto mosaico en las sociedades modernas industriales presenta un claro desacoplamiento entre la distribución de las horas de actividad humana y los requerimientos de energía exosomática, es decir, la energía utilizada por el conjunto de artefactos de la tecnosfera. Los sectores primario y secundario usan una pequeña fracción del conjunto de las horas de actividad humana disponibles en la sociedad. Por ejemplo, de 8.760 horas per cápita anuales, el conjunto de los 28 países miembros de la UE destinaba de media en 2015 tan sólo 40 horas a agricultura y 160 horas a industria mientras se destinaban más de 520 horas a servicios (Velasco-Fernández et al., 2019). Sin embargo, necesitan grandes inversiones de energía exosomática, hecho que se constata en los altos ratios metabólicos (energía por hora de actividad humana) de estos sectores (en el caso de la UE-28 mencionado anteriormente el sector industrial llega a consumir más 400 MJ/h). En general, elevados ratios metabólicos están asociados a altos niveles materiales de vida y a la generación de presiones ambientales resultantes de los elevados requerimientos en materiales y energía del proceso económico (Velasco-Fernández et al., 2018).

3.9. *Efecto Sudoku*

MuSIASEM facilita una representación multidimensional, del patrón metabólico del sistema socioeconómico considerado, similar a la cuadrícula del popular juego matemático "sudoku". La información relacional de las gramáticas es condensada para obtener una cuantificación de las variables fondo (generalmente actividad humana y usos del suelo si bien la potencia instalada también puede ser considerada) y las variables flujo (básicamente energía, agua, alimentación, emisiones, residuos y flujos monetarios) asignadas a los diferentes compartimentos funcionales jerárquicamente ordenados. Con ello obtenemos un diagnóstico de los requerimientos biofísicos tanto al nivel del sistema como totalidad como de los diferentes sectores económicos (agricultura, energía y minería, manufactura y construcción, servicios y gobierno y sector doméstico). También, descendiendo en el nivel de observación, podemos obtener información biofísica acerca de procesos o tareas específicas dentro de los diferentes subcompartimentos económicos (por ejemplo el uso de energía y otros recursos en diferentes explotaciones agrícolas o en el sector turístico). En esencia, la caracterización facilitada por MuSIASEM permite obtener indicadores contextualizados que nos informan sobre qué tipos de energía y recursos son utilizados, por quién, cómo y para hacer qué.

MuSIASEM utiliza tanto variables intensivas como extensivas. Las primeras son ratios flujo-fondo que nos dan información sobre características metabólicas (tasas, por hora; densidades, por hectárea e intensidades, por kilovatio). Por su parte, las variables extensivas nos dan una idea del tamaño de los diferentes partes del sistema respecto a su totalidad y de sus respectivos requerimientos biofísicos. Un aspecto clave de MuSIASEM es el uso de indicadores "por hora de actividad humana" o "por hectárea de uso del suelo" aplicado a los diferentes compartimentos funcionales. La descomposición de la tradicional caracterización "per cápita" o "por hectárea" en subcategorías funcionales de usos del tiempo y del espacio permiten una mejor comprensión del metabolismo del sistema bajo estudio a la vez que facilita la simulación de escenarios. Además, es posible utilizar valores de referencia, establecidos en la literatura sobre la metodología, bajo los cuales evaluar el desempeño económico o biofísico del sistema estudiado. Así, podemos comparar la dimensión económica de un determinado compartimento socioeconómico, por ejemplo energía consumida por hora en el sector servicios, o su dimensión ecológica, por ejemplo consumo de agua en el sector agrícola por hectárea, con valores promedio o con otros territorios donde se están realizando estudios similares (Sorman 2015).

El modo en que los datos están representados, las filas muestran los sucesivos niveles jerárquicos y columnas las diferentes dimensiones de análisis, genera tres tipos de limitaciones o restricciones útiles a la hora de analizar el patrón metabólico o simular escenarios. En primer lugar aparece una restricción vertical que apunta a la competición por recursos. Los diferentes factores de producción (elementos fondo y flujo) en una sociedad son limitados de manera que si un compartimento funcional incrementa su utilización otros compartimentos deben reajustar su uso. En segundo lugar, la restricción horizontal hace referencia al límite en la posibilidad de sustituir factores de producción. Así, la combinación de factores debe ser tal que permita a cada fila, es decir, cada compartimento funcional, realizar su cometido. Finalmente, al igual que en el popular pasatiempo, existe una restricción de bloques. Los compartimentos que engloban el hiperciclo y aquellos que constituyen la parte disipativa deben mantener un equilibrio dinámico ya sea generado internamente o con la masiva importación de recursos (Giampietro y Bukkens 2015).

4. Consideraciones finales.

Los principales retos a los que se enfrenta la humanidad en el siglo XXI, entre los que se encuentran el cambio climático, la transición hacia un sistema energético basado en renovables o la pérdida de la biodiversidad, son biofísicos. Estos desafíos requerirán una redefinición del papel de las narrativas económicas en el seno de la sociedad así como un cambio radical en las instituciones y un reajuste de las prácticas sociales. Asimismo, las iniciativas que se han articulado para dar respuesta a estas emergencias, recogidas en los Objetivos del Desarrollo Sostenible (ODS), necesitan de la integración de información procedente de diferentes dimensiones (la biofísica, la económica, la social) y escalas de análisis. La situación actual precisa de respuestas desde la economía ecológica (EE). Para ello se hacen necesarios cambios en su aparato conceptual y metodológico que abandonen su adhesión a viejos paradigmas y se centren en una perspectiva basada en la complejidad que ponga los fundamentos biofísicos del proceso económico en el centro de la agenda de investigación.

En esta comunicación se ha presentado a la metodología MuSIASEM como una herramienta epistemológica que facilita una caracterización en esta dirección. Desde una ontología básica consistente en sistemas complejos adaptativos múltiplemente interdependientes, la metodología permite realizar un diagnóstico multinivel de los requerimientos de energía y materiales necesarios para el mantenimiento y la reproducción de los sistemas socio-ecológicos. En este sentido es posible obtener una serie de indicadores base, a partir de los cuales poder discutir posibles vías de transición hacia un desarrollo más sostenible. Además, la metodología se alinea bien con preceptos básicos de la EE como son el uso de indicadores provenientes de diferentes dimensiones y la inconmensurabilidad de valores.

Si bien MuSIASEM es una herramienta eminentemente cuantitativa, sus fundamentos teóricos nos invitan a reflexionar sobre que, en lo que se refiere a la sostenibilidad, hacer más y más números no tiene porqué ser la respuesta. La sostenibilidad de las sociedades humanas parece requerir un equilibrio sutil entre eficiencia, hacer más de lo mismo bajo una definición de identidad dada, y adaptabilidad, es decir, cambiar la identidad del sistema ante cambios en las condiciones ambientales. En otras palabras, no es el mundo exterior el que se tiene que adaptar a nuestros requisitos y deseos. Al contrario, es necesario adaptar nuestras expectativas a las limitaciones impuestas por el mundo exterior, lo que implica un proceso reflexivo y conflictivo sobre el modo en que realizamos nuestro particular proceso semiótico. A su vez, esta consideración nos invita a ser escépticos con posturas excesivamente optimistas con respecto al uso unilateral de innovaciones tecnológicas como medio para resolver los problemas de sostenibilidad. Estos últimos, también requerirán cambios sociales y culturales que se materializarán en nuevas reconfiguraciones de la sociedad y nuevas prácticas sociales. En este sentido, se hará necesario el saber aprender a balancear los intereses y convivir con los pros y los contras de las soluciones, sin dejar de reflexionar sobre los nuevos problemas que surgen de forma democrática y asumiendo que, si bien sólo podemos aspirar a cambiar los problemas, al menos esto se puede llevar a cabo de una forma reflexiva y bien informada.

En definitiva, el análisis del patrón metabólico nos permite una discusión informada sobre el proceso de cambio de las sociedades humanas. En este proceso, las restricciones biofísicas afectan el espacio de decisión. Si como afirma Tanuro (2020), no hay libertad sin que exista conciencia de los límites, MuSIASEM nos dirige hacia percepciones y representaciones en esa dirección.

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Referencias bibliográficas

-Ahl, Valerie y Allen, T.F.H. (1996): *Hierarchy Theory*, New York: Columbia University Press.

-Allen, T.F.H. y Starr, T. (1982): *Hierarchy: Perspectives for Ecological Complexity*, Chicago: University of Chicago Press.

-Bland, William L. y Bell, Michael M. (2007): “A Holon Approach to Agroecology”, *International Journal of Agricultural Sustainability* 5 (4), pp 280-94.

-Capra, Fritjof (1996): *La Trama de La Vida*, Barcelona: Anagrama, 2009.

-Chomsky, Noam (1998): *On Language*, New York: The New Press.

-D'Alisa, Giacomo; Di Nola, Maria Federica y Giampietro, Mario (2012):" A multi-scale analysis of urban waste metabolism: density of waste disposed in Campania", *Journal of Cleaner Production* 35, pp. 59-70.

-Daly, Herman E. (1977): *Steady State Economy*, San Francisco: Freeman.

-Dalyn Herman E. (2005): "Economics in a full world", *Scientific American* 293, pp. 78-85.

-Daly, Herman E. (2019): “Some Overlaps between the First and Second Thirty Years of Ecological Economics.”, *Ecological Economics* 164, pp.106-372.

-Funtowicz, Silvio O. y Ravetz, Jerome (1993): “Science for the Post-Normal Age.”, *Futures* 25 (7), pp. 735-55.

-Georgescu-Roegen, Nicholas (1971): *The Entropy Law and the Economic Process*, Cambridge: Harvard University Press.

-Gerber, Julien François y Scheidel, Arnim (2018): “In Search of Substantive Economics: Comparing Today’s Two Major Socio-Metabolic Approaches to the Economy – MEFA and MuSIASEM.”, *Ecological Economics* 144, pp. 186-94.

-Giampietro, Mario (1994): “Using Hierarchy Theory to Explore the Concept of Sustainable Development.”, *Futures* 26 (6), pp. 616–25.

-Giampietro, Mario (2003): *Multi-Scale Integrated Analysis of Agro-Ecosystems*, Boca Raton: CRC Press.

-Giampietro, Mario (2019a): “On the Circular Bioeconomy and Decoupling: Implications for Sustainable Growth.”, *Ecological Economics* 162, pp. 143-156.

-Giampietro, Mario (2019b): “The Quality of Scientific Advice for Policy: A Few Insights from Complexity.”, *working paper* del proyecto MAGIC financiado bajo el programa H2020-GA 689669.

Disponible en: https://magic-nexus.eu/sites/default/files/files_documents_repository/quality-scientific-advice-for-policy_magic-report_may2019_0.pdf Consultado el 24 de mayo de 2020.

-Giampietro, Mario; Aspinall, Richard J.;Ramos-Martin, Jesús y Bukkens, Sandra G.F. (2014): *Resource Accounting for Sustainability Assessment: The Nexus between Energy, Food, Water and Land Use*, New York: Routledge.

-Giampietro, Mario, y Bukkens, Sandra G.F. (2015): "Analogy between Sudoku and the Multi-Scale Integrated Analysis of Societal Metabolism.", *Ecological Informatics* 26, pp. 18-28.

-Giampietro, Mario y Funtowicz, Silvio O. (2020): "From elite folk science to the policy legend of the circular economy", *Environmental Science & Policy* 190, pp. 64-72.

-Giampietro, Mario y Mayumi, Kozo (2010): "Multi-Scale Integrated Assessment of Societal Metabolism: Introducing the Approach.", *Population and Environment* 22, pp. 109-53.

-Giampietro, Mario y Mayumi, Kozo (2018): "Unraveling the Complexity of the Jevons Paradox: The Link between Innovation, Efficiency, and Sustainability.", *Frontiers in Energy Research* 6, pp. 1-13.

-Giampietro, Mario; Mayumi, Kozo y Sorman, Alevgül H. (2012): *The Metabolic Pattern of Societies : Where Economists Fall Short*, New York: Routledge.

-Giampietro, Mario; Mayumi, Kozo y Sorman, Alevgül H. (2013): *Energy Analisys for a Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism,* New York: Routledge.

-Giampietro, Mario y Renner, Ansel (2020): "The Generation of Meaning and preservation of Identity in Complex Adaptive Systems-The LIPHE4 Criteria". En *Proceedings of the "Tenth International Conference on Complex Systems",* Nashua: Springer-Verlag.

-Haberl, Helmut; Wiedenhofer, Dominik; Pauliuk, Stefan; Krausmann, Fridolin; Müller, Daniel B. y Fischer-Kowalski, Marina (2019): "Contributions of Sociometabolic Research to Sustainability Science.", *Nature Sustainability* 2 (3), pp. 173-184.

-Harvey, David (2010): *A Companion to Marx's Capital*, London-New York: Verso.

-Harvey, David (2018): "Universal Alienation.", *Journal for Cultural Research* 22 (2), pp. 137-50.

-Harvey, David (2019): *La Lógica Geográfica Del Capitalismo*. Benach, Núria y Albet, Abel (eds), Barcelona: Icaria editorial.

-Iberall, A.; Soodak, H. y Arensberg, C. (1980): "Homeokinetic Physics of Societies, A New Discipline: Autonomous Groups, Cultures, Polities." En *Perspectives in Biomechanics*, Real, H.; Ghista, D. y Rau, C. (eds), pp. 433-528, New York: Harwood Academic Press.

-Koestler, Arthur (1967):*The Ghost in the Machine*, New York: Macmillan Co.

-Lakoff, George (2010): "Why it Matters How We Frame the Environment.", *Environmental Communication*, 4 (1), pp. 70-81.

-Lotka, Alfred J. (1922): "Contribution to the Energetics of Evolution.", *Proceedings of the National Academy of Sciences* 8 (6), pp. 147-151.

-Luisi, Pier Luigi (2003): "Autopoiesis: A Review and a Reappraisal.", *Die*

Naturwissenschaften 90 (2), pp. 49-59.

-Martinez-Alier, Joan; Munda, Giuseppe y O'Neill, John (1998): "Weak Comparability of Values as a Foundation for Ecological Economics", *Ecological Economics*, 26 (3), pp. 277-286.

-Maturana, Humberto y Varela, Francisco (1980): *Autopoiesis and Cognition: The Realization of the Living,* Dordrecht: D. Reidel Publishing.

-McKinnon, Andrew (2010): “Energy and Society: Herbert Spencer’s ‘Energetic Sociology’ of Social Evolution and Beyond.”, *Journal of Classical Sociology* 10 (4), pp. 439-55.

-Melgar-Melgar, Rigo E. y Hall, Charles A.S. (2020): “Why Ecological Economics Needs to Return to Its Roots: The Biophysical Foundation of Socio-Economic Systems.”, *Ecological Economics* 169, pp. 106567.

-Naredo, José Manuel (1987): *La Economía En Evolución : Historia y Perspectivas de Las Categorías Básicas Del Pensamiento Económico,* Madrid: Siglo XXI, 4ºedición 2015.

-Pattee, H.H. (1995): “Evolving Self-Reference: Matter, Symbols and Semantic Closure.”, *Communication and Cognition-Artificial Intelligence* 12 (1-2), pp. 9-27.

-Pirgmaier, Elke y Steinberger, Julia K. (2019): “Roots, Riots and Radical Change-a Road Less Travelled for Ecological Economics.”, *Sustainability* 11 (7), 2001.
Disponible en:
https://www.mdpi.com/2071-1050/11/7/2001 Consultado el 25 de mayo de 2020.

-Plumecocq, Gaël (2014): "The second generation of ecological economics: How far has the apple fallen from the tree?, *Ecological Economics* 107, pp.457-468.

-Prigogine, Ilya y Nicolis, Grégoire (1977): *Self-Organization in Nonequillibrium Systems*, New York: Wiley.

-Renner, Ansel; Louie, A.H. y Giampietro, Mario (2020): "Cyborgization of Modern Social-Economic Systems: Accounting for Changes in Metabolic Identity". En *Proceedings of the "Tenth International Conference on Complex Systems",* Nashua: Springer-Verlag.

-Ripa, Maddalena y Giampietro, Mario (2017): “Report on Nexus Security Using Quantitative Story-Telling.”, *working paper* del proyecto MAGIC financiado bajo el programa H2020-689669.
Disponible en:
https://magic-nexus.eu/sites/default/files/files_documents_repository/magic-ga689669-d4.1-revision.pdf Consultado el 25 de mayo de 2020.

-Røpke, Inge (2004): “The Early History of Modern Ecological Economics.”, *Ecological Economics* 50, pp. 293-314.

-Røpke, Inge (2005): “Trends in de Development of Ecological Economics from the Late 1980s to the Erarly 2000s.”, *Ecological Economics* 55, pp. 262-290.

-Rosen, Robert (1985): *Anticipatory Systems: Phylosophical, Mathematical and Methodological Foundations,* New York: Pergamon Press.

-Rosen, Robert (2000): *Essays on Life Itself*, New York: Columbia University Press.

-Scheidel, Arnim y Farrell, Katherine N. (2015): "Small-scale cooperative banking and the production of capital: Reflecting on the role of institutional agreements in supporting rural livehood in Kampot, Cambodia", *Ecological Economics* 119, pp. 230-240.

-Sorman, Alevgül H. (2015): “Societal Metabolism.” En *Degrowth: A Vocabulary for a New Era*, D’Alisa, Giacomo; Demaria, Federico y Kallis, Giorgio (eds), New York: Routledge, pp. 41-44.

-Spash, Clive L. (2015): “The Content, Direction and Philosophy of Ecological Economics.” En *Handbook of Ecological Economics*, Martínez-Alier, Joan y Muradian, Roldan (eds), Cheltenham: Edward Elgar Publishing, pp. 26-47.

-Spash, Clive L. (2020): “A Tale of Three Paradigms: Realising the Revolutionary Potential of Ecological Economics.”, *Ecological Economics* 169, pp.106518.

-Steffen, Will; Rockström, Johan; Richarson, Katherine; Lenton, Timothy M.; Folke, Carl; Liverman, Diana; Summerhayes, Colin P. et al. (2018): “Trajectories of the Earth System in the Anthropocene.”, *PNAS* 115 (33), pp. 8252-8259.

-Tainter, Joseph A. (1988): *The Collapse of Complex Societies*, Cambridge: Cambridge University Press.

-Tainter, Joseph A. (2006): “Social Complexity and Sustainability.”, *Ecological Complexity* 3 (2), pp. 91-103.

-Tanuro, Daniel (2020): “El Ecosocialismo Como Imaginario. Nuevos Paradigmas y Estrategias Frente Al Desastre.” En Vindel, Jaime (dirección) *Hacia Una Nueva Imaginación Ecosocial. Narrativas y Transiciones Ante La Crisis de Civilización*. Seminario llevado a cabo en Barcelona (5, 6, 7 de marzo de 2020).

Disponible en:
https://www.macba.cat/es/exposiciones-actividades/actividades/hacia-nueva-imaginacion-ecosocial Consultado el 25 de mayo de 2020.

-Ulanowicz, Robert E. (1986): *Growth and Development: Ecosystem Phenomenology*, New York: Springer-Verlag.

-UN Environment (2019): *Global Environment Outlook (GEO-6): Healthy Planet, Healthy People,* Nairobi.

Disponible en:
https://wedocs.unep.org/bitstream/handle/20.500.11822/27539/GEO6_2019.pdf?sequence=1&isAllowed=y Consultado el 25 de mayo de 2020.

-Velasco-Fernádez, Raúl; Chen, Lei; Pérez-Sánchez, Laura y Giampietro, Mario (2019): "Multi-scale integrated comparison of the metabolic pattern of EU28 and China in time.", *working paper* del proyecto EUFORIE financiado bajo el programa H2020-649342.

Disponible en:
https://sites.utu.fi/euforie/wp-content/uploads/sites/182/2019/05/649342_EUFORIE_D4.4.pdf Consultado el 30 de mayo de 2020.

-Velasco-Fernández, Raúl; Dunlop, Tessa y Giampietro, Mario (2020): “Fallacies of Energy Efficiency Indicators: Recognizing the Complexity of the Metabolic Pattern of the Economy.”, *Energy Policy* 137, pp. 111089.

-Velasco-Fernández, Raúl; Giampietro, Mario y Bukkens, Sandra G.F. (2018): “Analyzing the Energy Performance of Manufacturing across Levels Using the

End-Use Matrix.", *Energy*, 161, pp. 559-572.

-Wallace, Rob; Liebman, Alex; Chaves, Luis Fernando y Wallace, Rodrick (2020): "COVID-19 and Circuits of Capital.", *Monthly Review* (May 01, 2020).

Disponible en: https://monthlyreview.org/2020/05/01/covid-19-and-circuits-of-capital/ Consultado el 25 de mayo de 2020.

-White, Leslie A. (1943): "Energy and Evolution of Culture." *American Anthropologist* 14, pp. 335-356.

-Zipf, George Kingsley (1941): *National Unity and Disunity: The Nation as a Biosocial Organism*, Bloomington, IN: Principia Press.

-Zipf, George Kingsley (1949): *Human Behaviour and the Principle of Least Effort: An Introduction to Human Ecology*, Cambridge: Addison-Wesley.

Ecological Economics
Limits and meaning matter: MuSIASEM as a biophysically grounded framework for analyzing the sustainability of social-economic systems.
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Abstract:	Highlights - New epistemological tools are needed to envision a post-growth caring economy. - MuSIASEM is a meaningful method to study the biophysical roots of the economy. - Considering multiple dimensions, scales and levels is crucial to identify optimization side-effects. - Holarchies, hypercycles and openness are crucial relational characteristics of metabolic systems. - Meaning is as important as energy and material constraints to determine societal sustainability.
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Opposed Reviewers:	

Limits and meaning matter: MuSIASEM as a biophysically grounded framework for analyzing the sustainability of social-economic systems.

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Highlights:

- New epistemological tools are needed to envision a post-growth caring economy.

- MuSIASEM is a meaningful method to study the biophysical roots of the economy.

- Considering multiple dimensions, scales and levels is crucial to identify optimization side-effects.

-Holarchies, hypercycles and openness are crucial relational characteristics of metabolic systems.

- Meaning is as important as energy and material constraints to determine societal sustainability.

Abstract:

The biophysical challenges to sustainability are getting more evident now that the global economy moved from an empty world to a full world. Acknowledging the existence of biophysical limits requires a total reconfiguration of our current pattern of material and energy use, a radical change in institutions and a re-adjustment of current social practices. At the moment the narratives proposed by orthodox economics (OE) refuse to acknowledge this fact. This explains why processes beyond human control associated with these limits are excluded from sustainability discussions. However, the lack of results in the fight to avoid irreversible damage to the biosphere is exposing the nature of the crisis: urgent action is needed and there are plenty of proposals, but adequate analytical tools are lacking. This paper presents a novel accounting framework, Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) providing a different analytical approach to sustainability, based on complexity. It integrates different aspects relevant for sustainability characterized across dimensions, levels and scales of analysis. The paper provides a critical check on the robustness of the theoretical foundations of MuSIASEM examining the concepts combined in the analytical framework. Finally, by noticing that MuSIASEM is faithful to the original principles of ecological economics (EE) the paper concludes that this methodology is consistent with the ambitious founding plan of EE.

Keywords: MuSIASEM, Sociometabolic Research, Sustainability, Ecological Economics.

1. Introduction

The cult movie "They Live" (Carpenter, 1988) tells the adventures of an unnamed drifter, who discovers through special sunglasses, that the ruling class are aliens hiding their appearance and manipulating people to spend money, breed and accept the status quo with subliminal messages in mass media. The use of these sunglasses allows the hero to understand veiled aspects of reality and to take action to derail alien plans. As a matter of fact, the movie points at a well-known problem in social theory. Even without the presence of alien invaders, the selection of what are the relevant aspects of reality that should be considered by a given society at the moment of deciding action depends on the choice of narratives about the state of affairs reflecting particular interests. This selection of narratives used to frame relevant issues becomes especially tricky in modern complex societies where individuals are expressing a variety of concerns, hopes, fears, and have access to a fragmented, contradictory and marginal knowledge of the factors determining their social practices. This entails that in sustainability we deal with "wicked problems" (Rittel and Webber, 1973).

Perceptions are shaped by the story we identify with (Macy and Johnstone, 2012). The point to be made here is that the present dominance of the narratives proposed by orthodox economics (OE) has produced a distorted worldview where the dependence of social and economic structures of a biophysical reality is blurred and systematically ignored (Spash and Smith, 2019). The object of study and the definition of social wealth are limited and reduced to the self-referential universe of exchange values determining a separation between "subjective" (economic) and "objective" (biophysical) scarcity (Naredo, 2015). In turn, the two paradigmatic theories — i.e. economic growth and price-making markets (Spash, 2020) — contribute to the legitimization of policies that are seriously detrimental to the poor and destroy ecosystems and life conditions (Røpke, 2005). According to Giampietro and Funtowicz (2020), the success of OE is explained not because of its ability to provide insights about how to guide action in relation to sustainability of modern societies, but rather because its ability to filter out uncomfortable knowledge that could destabilize the actual structure of power. Thus, the systemic application of OE narratives keeps the sustainability debate depoliticized (Velasco-Fernández, 2020) and allows to envision the future as if the "business as usual" state is the best of the possible states in which society is "saved" by smart technologies. This is why OE narratives have to be embedded in policy legends as the circular economy, zero-emissions or zero-waste processes, the decoupling or green growth. Consequently, a constant "social construction of ignorance" subjected to the systemic exclusion of "uncomfortable knowledge" (Rayner, 2012) is produced, removing from the sustainability discussions robust knowledge claims — i.e. thermodynamic principles. In this way, the biophysical challenges determined by the fact that global economy moved from operating in an empty world to a full world (Daly, 2019a, 2005) can be systematically ignored.

Ecological economics (EE) came into being out of a deep concern that OE's applications to the environment were insufficient to effectively deal with modern environmental crisis (Pirgmaier and Steinberger, 2019; Røpke, 2004). After more than forty years of the establishment of EE, it is becoming more and more clear that economic growth is threatening planetary equilibrium (Steffen et al., 2018). Environmental crisis, has been widely recognized (IPBES, 2019; UN Enviromemnt, 2019) and the time to avoid irreversible processes is running out (Masson-Delmotte et al., 2018). Despite some buds of political commitment[8] and the insurgence of social movements (e.g. Fridays for Future or Extinction Rebellion), most of institutions and citizenry remains blind to the dependence of our economies on the natural macro system. The social construction of ignorance entails that our society tends to ignore the existence of processes beyond human control that impose limits. This implies that new visions are necessary to detoxify us from the influence of OE narratives and reconnect our actions with the consequences they produce. On this line, several scholars have shown the need of EE to return to its original roots by placing the biophysical understanding of social-economic systems and the rejection of OE's core principles at the center of its research agenda (Daly, 2019b; Hagens, 2020; Melgar-Melgar and Hall, 2020; Pirgmaier and Steinberger, 2019; Spash, 2020).

[8] EU Parliament declared a climate and environmental emergency in Europe and globally on November 28, 2019.

This paper discusses how Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) contributes to transform, similar to the special glasses from Carpenter's movie, the existing perceptions and representations of society-nature relations into a more holistic one. MuSIASEM is an innovative method to better characterize how societies use natural and human-created goods and how social-economic systems simultaneously depend on and place pressures on processes taking place in ecosystems. This biophysically grounded framework is open to pluralities of values and concerns, which makes the methodology an excellent candidate to support the ambitious founding plan of EE. MuSIASEM is one of the main methodological approaches found in sociometabolic studies (González de Molina and Toledo, 2014; Haberl et al., 2019). According to Gerber and Scheidel (2018), Material and Energy Flow Analysis (MEFA) and MuSIASEM are today the two major sociometabolic approaches for the substantive ("in kind") study of the economy as a whole, not only focusing on a particular resource use. Yet, the originality of MuSIASEM lies in having a robust theoretical basis as a consequence of a sophisticated combination of concepts belonging to complex systems science (Giampietro, 2019a; Giampietro et al., 2014, 2013, 2012; Giampietro and Renner, 2020; Renner et al., 2020b) which can deal with the epistemological challenge associated with the consideration of different aspects relevant for the discussion over sustainability. In particular the adoption of the flow-fund model of Georgescu-Roegen (1971) allows the MuSIASEM accounting framework to compare the size of the fund elements used by the economic process in its different functional compartments with the size of the ecological fund elements affected by the expression of the societal metabolism.

The current social and health crisis caused by Covid-19 has highlighted the fragility of existing economies and the perverse effects produced by an excessive pressure on regional ecosystems (Wallace et al., 2020). Hopefully, the negative effects of progressive environmental degradation will push for new cognitive processes questioning the role of OE narratives, the usefulness of actual institutions and the viability of current social practices. In this new emerging context, the mission of ecological economists should be to facilitate systemic change (Pirgmaier and Steinberger, 2019) from a position of counterfactual hope (Riechmann, 2017), i.e. moving from "persist despite everything" to "respond appropriately when conditions arise". Transforming the economy to a post-growth caring one, which takes care of people and nature, while adopting a flexible approach requires exploring the bottom-up ability of self-organization using alternative epistemological tools like the one presented here.

The paper is organized as follows: section two presents MuSIASEM's basic ideas on the characterization of the social-economic system, the economic process and the sustainability predicament. Section three discusses relevant theoretical concepts needed to develop applications based on the richness of its theoretical foundations. Each concept emphasizes a pertinent feature or level of observation to be considered. Section four discusses strengths and weaknesses of MuSIASEM. To finish, section five closes with some final considerations.

2. MuSIASEM: new perspectives for current challenges.

2.1. About social-economic systems.

From MuSIASEM perspective, social and natural systems are complex adaptive systems (Gell-Mann, 1994; Holland, 2006, 1995) and should be studied considering social and natural systems as entangled (Giampietro, 2019a). This point of view recognizes the contribution coming from the functioning of ecosystems as decisive not only because of the provision of natural resources and as a disposal sink for wastes, but even more because they provide a variety of ecological services without which human societies could not flourish (e.g. maintenance of the composition of the atmosphere, amelioration of climate, operation of the hydrological cycle, generation of soils, etc.). When considering the functioning of such a system, we find a complex network of processes and a dense web of relations that are impossible to quantify in comprehensive representations let alone by using monetary valuations (Giampietro and Funtowicz, 2020; Røpke, 2005).

Considering a system as complex presents several epistemological challenges. On one hand, the behavior of the whole is not evident from the study of its parts (Cilliers, 1998). The pattern must be taken into account, understood as a specific configuration of relationships (Capra, 1996). In relation to this challenge MuSIASEM applies a systemic thinking framework where the social-economic system is considered an integrated whole whose properties are determined by the dynamic connections among functional and structural elements. The study of the relationships is organized in two descriptive domains: (i) the relationships among system's components inside the border determining its *state*; (ii) the relationships among the system (seen as a whole) and its surrounding determining its *environmental pressures*. On the other hand, complexity implies recognizing the role of the decisions of the observer in what is observed uncovering the co-existence of different perceptions and representations across different scales (Ahl and Allen, 1996). An approach acknowledging the implication of complexity has to take into consideration the unavoidable existence of social and technical incommensurability (Munda, 2008). The existence of different social actors, having contrasting and legitimate values, perceptions and interests (social incommensurability) and the impossibility of reducing the various useful representations into a single quantitative model (technical incommensurability) requires the development of new approaches to the use of science in the process of governance (Saltelli and Giampietro, 2017).

With the aim of obtaining a characterization as complete as possible of a social-economic system understood as complex system, MuSIASEM integrates information from different dimensions (economic, biophysical, demographic and ecological) and considers different levels of analysis (the whole, compartments and sub-compartments) whose characteristics can be integrated across different spatial and temporal scales (Giampietro and Mayumi, 2010). This analytical framework represents a radical departure for the study societal metabolism contesting the traditional reductionist approach based on the adoption of a single scale and a single dimension of analysis at a time.

MuSIASEM enables a narrative where the performance of the whole social-economic system is tied to the "emergent property" determined by the interaction of its constituent components, i.e hierarchically organized, lower-level functional components (e.g. economic sectors and subsectors) made up of structural elements expressing physical processes. The emergent property is represented by the ability of the society to maintain its identity, or in other words, to reproduce and adapt according to its internal values and aspirations, while interacting with its context (Giampietro et al., 2012). The constituent components, on the other hand, express different functions, associated with a wide variety of useful outputs or end uses, limited by the thermodynamic characteristics of its local combination of production processes. For example, the agriculture sector generates several useful outputs: (i) the biomass input to the energy sector; (ii) the raw material inputs to the manufacture sector; (iii) food inputs to the service sector; (iv) food input to the household sector; while covering (v) the internal requirement of agricultural inputs (e.g. seeds and feeds for animals) for agricultural production. The supply of all these inputs is determined by the characteristics of the structural elements that make up the agriculture sector, i.e. productive capacity of different types of farms determined by technical viability, and the availability of ecological services, i.e. the availability of the production factors, such as soil, solar radiation or biodiversity, made available by natural processes.

The method links the perception of an economic system with concepts such as interdependence and complementarity. In this framework, a social-economic system is considered a relational metabolic network in which constituent components stabilize each other in an impredicative set of relations (Renner et al., 2020b). Social-economic systems have a self-referential pattern of organization determining a network of relationships in which the function of each component has to be integrated and coordinated to sustain and reproduce the network. Thus, constituent components of an archetypical modern social-economic system depend on each other in terms of essential inputs: (i) the household sector uses inputs produced by all the other constituent components to reproduce itself (i.e. nurturing and care work) and to supply hours of human activity (labor and consumption) to the rest of constituent components; (ii) the primary sectors use human activity coming from the household, primary sources coming from the environment, and secondary inputs coming from the other constituent components to supply secondary inputs of food, energy and raw materials to the others; (iii) the manufacturing sector and construction sector uses human activity and secondary inputs to supply technology and infrastructures to the entire society; and (iv) the service and government sector uses human activity and secondary inputs to reproduce institutions and maintain the quality of life of people (Velasco-Fernández et al., 2020a).

2.2. About the economic process.

Inspired by the work of Georgescu-Roegen (1971), MuSIASEM also invites to rethink the final cause of the economic process. The great biophysical economist considered the enjoyment of life as the ultimate purpose of the economic process. Thus "value" derives from the perceptions, emotions and feelings of the "physic structure" of the society (Luhmann, 1995), associated with the production and consumption of goods and services in societal practices. Following the same line of reasoning, the ultimate goal of the economic process in MUSIASEM is not that of producing as much as possible goods and services (ecosystems and households also produce goods and services), but to ensure the maintenance, reproduction and adaptability of constituent components. The final cause of the economy is not only the reproduction of itself, i.e. its biophysical bases or structural elements (mainly human population, power capacity and productive land) but also the reduction of the stress of its individual members by addressing their concerns, hopes and fears. Changing this perspective on the final cause of the economy shifts attention from productivism to a different set of essential factors determining sustainability. This shift is in line with a vision of economics as a science of social provisioning which seeks to understand how societies organizes the flow of goods and services necessary to maintain and reproduce themselves in the context of historically specific systems and structures (Spash, 2020; Pirgamier and Steinberger, 2019).

With the above in mind, the metabolism of a social-economic system is not a metaphor but a fact (Giampietro et al., 2020). Social-economic systems are metabolic-repair systems of the type explored in relational biology (Renner et al., 2020b). They can maintain and adapt their identity, i.e. its structural elements, its functional elements and the emergent property providing a desirable standard of living for the people living in society, because a process of replication, metabolism and repair.

2.3. About sustainability.

MuSIASEM opens the way for a quantitative and qualitative contextualization of the sustainability of social-economic systems based on the study of the metabolic pattern. The metabolic pattern refers to the various processes of conversion of energy and materials inputs, used to reproduce structural elements and express the expected functions. This can be expressed as flow/fund ratios and fund allocation patterns (Velasco-Fernández et al., 2020b). More specifically in relation to the fund human activity (metabolic rates and societal human time distribution) and in relation to the fund land use (metabolic densities and land use distribution) of the various constituent components (agricultural, industrial, residential, etc.). As regards to the environmental pressures, resource requirements can be specified for different land uses.

If sustainability is understood as the compromise of human societies to adjust their expectations to collective care of lives within limits, the analysis of the metabolic pattern allows an approach which generates different indicators referring to different levels of observation capable of addressing different sustainability concerns. In this way it becomes possible to integrate different views of sustainability:

1. An external view related to the concept of feasibility and associated to processes outside human control. Feasibility checks the compatibility of the *environmental pressures* associated with the metabolic pattern of society with the existence and severity of external biophysical constraints. This involves constraints that result from the interaction of the social-economic system with ecological systems, both on the supply (e.g. primary sources as oil, water or minerals) and sink side (e.g. wastes and emissions as greenhouse gases or plastic waste). This view is translated into a quantitative assessment associated with the *environmental pressure matrix*.

2. An internal view related to the concept of viability and associated to processes under human control. Viability checks the severity of internal biophysical constraints and economic constraints operating inside the social-economic system. These constraints include human capital, technological capability, economic viability and labor supply/shortage. The requirement and availability of labor are also associated with socio-demographic variables and the terms of trade (Pérez-Sánchez et al., 2020). Viability requires characterizing the *state*, i.e. the internal metabolic characteristics of structural and functional compartments (Giampietro et al., 2020). This

view is translated into a quantitative assessment associated with the *end-use matrix* based on the analysis of the use of secondary inputs, i.e. energy carriers, blue water and processed materials (Velasco-Fernández et al., 2018).

3. A normative view related to the concept of desirability. Desirability refers to the perceived acceptability of the living conditions associated with the expression of the metabolic pattern: social practices associated with affective relations are entangled with end uses associated with technical relations. This implies that in order to assess desirability it is necessary to extend the analysis beyond biophysical variables and economic narratives, by considering also matters of values, desires, belief as well as cultural, social and political arrangements. Addressing the desirability of the metabolic pattern of a social-economic system requires a reflection on the identity of the society which is preserved. A reflection that call for a post-normal science rationale (Funtowicz and Ravetz, 1993).

MuSIASEM establishes a framework of analysis capable of establishing a set of expected relations over these different aspects of sustainability (feasibility, viability and desirability). These different aspects generate non-equivalent and non-reducible definitions of constraints or limits of different nature. To this end, the approach uses a toolkit of an interrelated set of matrices. MuSIASEM toolkit supplies an integrated, multi-scale, quantitative representation of the functioning of the metabolic pattern that explicitly considers also the degree of openness of the social-economic system determined by trade. This tool-kit can be used: (i) in a diagnostic mode to identify critical aspects in the form of indicators that can be tailored on relevant concerns (e.g.Cadillo-Benalcazar et al., 2020b) ; and

(ii) in anticipatory mode by exploring scenarios based on the adoption of benchmarks (e.g. Renner et al., 2020a). Because of the consideration of the effects of the externalization (the degree of openness), the toolkit characterizing the factors determining the state and the pressure is organized on four matrices. Two different types of matrices are used to characterize the factors of viability (Velasco-Fernández et al., 2020a), observed inside the border — the *internal end-use ma*trix — and observed outside the border — the *externalized end-use matrix*. And two matrices are used to characterize the factors of feasibility, observed inside the border — the *internal environmental pressure matrix* — and observed outside the border — the *external environmental pressure matrix* (Giampietro et al., 2020; Renner et al., 2020a; Ripa et al., 2021). All these tools make possible to identify the key funds conforming socio-ecological system and their interdependences and maintenance cost thorough their stock/flow, flow/fund and fund/fund relations, making possible a biophysical accountability of care and meaning crucial to discuss about systemic changes.

In conclusion, in a full world where all parts are connected, reducing pressures in relation to just one of the ecological limits usually translates into the creation of new pressures on other limits. In the same way, the solution of a sustainability problem of a social-economic system through the externalization to other social ecological systems represents just a displacement of the problem (Ashukem, 2020). In this sense the study of the sustainability of human systems presents evident challenges that require the development of new analytical approaches. This is the goal of MuSIASEM.

3. Theoretical concepts.

This section introduces and discusses common theoretical concepts in the literature on MuSIASEM. Each of them comes from different roots within the tree of complexity science and each one touches on a key aspect to consider. Table 1 summarizes its main characteristics.

Table 11. Common theoretical concepts in the literature on MuSIASEM

Theoretical concept	Field	Level of observation	Main characteristic
State-pressure relations	Non-equilibrium Thermodynamics (Prigogine and Nicolis, 1977; Prigogine and Glansdorf, 1971)	Dissipative structures	Social-economic systems are open systems whose structures and functions (the STATE) are stabilized by a continuous flow of inputs taken from the environment (energy and matter) and a continuous flow of outputs released to the environment (wastes and emissions), which leads to an acceptable PRESSURE on the environment.
Relational Analysis	Relational Biology (Rashevsky, 1935; Rosen, 2000, 2005; Louie, 2017)	Metabolic processor used to describe both structural and functional elements	A processor describes a pattern of expected relations (that can be defined at different levels) between profiles of inputs and profiles of outputs associated with the expression of a specific function using two categories of accounting: (1) in relation to the interaction with other parts inside the technosphere (secondary inputs and outputs); and (2) in relation to the interaction with the biosphere (primary flows on the supply and sink side).
Holon and holarchies	Hierarchy Theory (Ahl and Allen, 1996; Allen and Starr, 1982, Giampietro et al., 2006, Giampietro, 1994)	Semantic relations between structural and functional types across levels	Co-existence of relevant aspects of the system that are tangible (biophysical) and notional (meaningful representation) when perceiving and representing a complex system. The differences between types and instances, i.e. coupling of structural and functional types vs. realizations of structural and functional types, can be studied across different levels of organizations, preserving the coherence in the analysis.
Semiotic process	Biosemiotics (Patte, 1995; Barbieri, 2019; Kull et al., 2019; Emmecha and Kull, 2011)	The generation and preservation of meaning in the process of cognition	In order to be able to learn and adapt, human systems must have anticipatory models. The quality of the choices of concerns and problems to be addressed, alternatives to be considered and the policies to be implemented are determined in a political process that conditions the expression of the metabolic pattern.

Dynamic Energy Budget	Theoretical ecology (Ulanowicz, 1986)	Net energy supply and the complex organization of metabolic networks	Any metabolic system, including social-economic systems, has to invest energy in (i) getting energy (in the hypercyclic part); and (ii) expressing other required behaviors (dissipative part) such as maintaining and updating social institutions. The constraints determined by this dynamic equilibrium forces the allocation of flow and fund elements across the different constituent components expressing the metabolic pattern.

3.1. *State-Pressure relations.*

Different narratives developed in the field of complexity suggest a strong analogy between the processes of self-organization of ecological and social systems (Giampietro, 2019b; Giampietro and Renner, 2020; Odum, 1971; Simon, 1962). Both classes are composed of open systems which require the existence of favorable boundary conditions, their states associated with a large generation of positive entropy, and therefore considered as improbable according to classical thermodynamics. In fact, the existence of complex metabolic systems, such as a modern social-economic system, can only by explained under a perspective of non-equilibrium thermodynamics, using the concept of dissipative structure (Prigogine and Glansdorff, 1971; Prigogine and Nicolis, 1977). This concept entails that their functions and structures are stabilized by a continuous flow of inputs (energy and matter) taken from the environment and a continuous flow of outputs (wastes) released into the environment. Social-economic systems are dissipative in the sense that they have functional structures that cannot be associated with the stability of solids: they tend to degrade and disappear into the environment when the flow of inputs is interrupted. In consequence, these systems must be capable of monitor and react to changes in their surroundings in order to remain capable of using fluxes of negative entropy compensating their positive production. In particular, the fluxes of negative entropy available in the environment (favorable boundary conditions associated with needed primary resources) are used to sustain a process of exergy degradation (when the process of conversion of secondary resources into useful work can be carried out under expected and controlled conditions). That is, the *environmental pressure* sustained by the environment (-dSe) compensates for the positive entropy generation rates (+dSi) associated with the maintenance of the *state* of complex internal organization.

When economic and ecological systems are conceptualized in the same language of flows of energy and matter, it results obvious to state that human economy is embedded in the geobiosphere of the earth (Røpke, 2005). The concept of state-pressure relations poses a vision on how human systems organize their energy and material exchange with their natural environment in order to stabilize the entropic process to which all living systems are subject. The consideration of this necessary relationship implies modifying our level of observation. The unity of study is not an isolated, self-sufficient economic system (with exchanges only considered in monetary terms) but a social-ecological system (SES) (Berkes et al., 2003; Holling, 2001), determined by the activities expressed by a given set of ecosystems (in the biosphere) and a given set of social actors and institutions (in the technosphere) (Giampietro, 2019a) .

MuSIASEM uses Georgescu-Roegen's flow-fund model, his most developed analytical contribution after the 1970s (Couix, 2018), under a framework of non-equilibrium thermodynamics in order to improve the accounting for state-pressure relations. The distinction between funds and flows is essential to define a metabolic system and characterize its metabolic pattern in quantitative terms. Funds are the underpinning components of SES, either biophysical (e.g. soils, aquifers) or societal (e.g. human activity or power capacity). Flows are transformed resources such as freshwater or energy carriers and include also wastes, i.e. unwanted by-products such as CO_2 emissions. Any SES can only sustain the production and consumption of flows at certain rates, without its funds becoming exhausted or degraded. By looking at the size of fund elements and their metabolic rate (flow rate per unit of fund) we can study state-pressure relations helping to identify unsustainable use of biophysical or societal resources (e.g. high rates of water extraction depleting an aquifer or long working hours that deplete a workforce).

The distinction between funds and flows makes the characterization generated by MuSIASEM a real metabolic study. The concept of metabolism applies only when what is metabolized (the flow) does affect and is affected by what is metabolizing it (the fund) (Giampietro et al., 2012). Thus, a metabolic study has to consider: (i) the nature of the dissipative structures of the system (the elements that have to be preserved and reproduced by the metabolic process to maintain the identity of the system); (ii) the types of specific flows they require (materials and energy that dissipate during the process), e.g. electricity is an energy input for a refrigerator but nor for an airplane, ham is food for a Protestant but not for an Islamic consumer; and (iii) the purpose of the considered metabolic pattern to the system. Moreover, the use of funds and flows allows differentiating between an external and internal vision since the pace of flows used by the funds elements is determined by the accessibility of adequate inputs flows from the environment (primary flows) and also by internal factors which have to do with the funds' capacity of processing available flows during the conversion (secondary inputs and outputs).

MuSIASEM offers an approach based on deep thermodynamic considerations which contrasts with those offered by other sociometabolic methods, like MEFA, influenced by OE's dominant idea of double-entry accounting system (González de Molina et al., 2019). The latter does not differentiate between different qualities and purposes of flows and provides a representation of the economic system as a "black box", focused on what gets into and out without considering the requirements of the various functional parts in terms of secondary flows. As a consequence, this approach ends up defining and characterizing metabolic patterns with misleading flow/flow indicators (Fiorito, 2013; Velasco-Fernández, 2017).

3.2. *Relational analysis*

The term relational analysis is based on the term relational biology (Louie, 2017; Rashevsky, 1935; Rosen, 2005, 2000) and refers to the existence of expected patterns expressed within metabolic networks. According to the unavoidable existence of state-pressure relations, any metabolic element of a SES has to operate across two interfaces: (i) inside the black-box between the parts — the interface between the local process and other technical processes where the inputs and outputs remain inside the border of the system (in the technosphere); and (ii) between the black-box and its context — the interface between technical processes and natural processes where the inputs and outputs cross the border with the biosphere (the primary flows). Therefore, the concept of metabolic processor represents a complexification in relation to conventional input-output analysis. A metabolic processor describes: (i) a pattern of expected relations between *profiles of inputs and profiles of outputs* (and not just an input and an output); (ii) both inputs and outputs exchanged by the parts *inside the black-box* (related to the *state*) and inputs and outputs exchanged by *the black-box with its context* (related to the *environmental pressure*); (iii) an *expected relation between a given set of profiles of inputs and outputs and the expression of a specific function* inside the metabolic pattern. These expected relations can be defined at different levels of analysis.

The use of metabolic processors enables the simultaneous use of two categories of accounting: (1) in relation to the interaction with other parts inside the technosphere, the inputs are the end uses of secondary flows and the quantities of societal funds needed for expressing the specific functions whereas the outputs refer to the useful contribution of the processor to the rest of the network; (2) in relation to the interaction with the biosphere the inputs are the primary flows coming either from non-renewable (stock depletion) or renewable (fund-flow supply) resources; and the outputs are the primary flows dumped into the biosphere in a sustainable (flow-fund sink) or unsustainable (sink filling) way. Therefore, the metabolic processor represents the external referent of the representation of a technical conversion. It can be imagined as an analogous of the concept of enzyme in the description of the metabolism of cells, or the concept of extended production function in biophysical economic analysis. Metabolic processors have the peculiar ability to combine in a coherent pattern (a data array) data that belong to non-equivalent descriptive domains (e.g. kWh of electricity vs. tones of green water) and therefore they describe the relation over quantities that are not reducible to each other using conventional inferential systems.

A relational analysis based on the concept of metabolic processors is used to describe the characteristics of structural and functional elements of a SES. This analysis can then be organized across levels by associating specific combinations of structural elements (at a given level) to the identity of functional elements (defined at the level above). For examples of quantitative analysis based on processors see (Cadillo-Benalcazar et al., 2020a; González-López and Giampietro, 2018, 2017; Parra et al., 2020, 2018; Serrano-Tovar et al., 2019).

3.3. *Holon and holarchies*

The term "holon" was proposed by Arthur Koestler (1967) to address the epistemological predicament consisting on that some entities are in many senses wholes but cannot be understood without recognition of contexts in which they interact. Clear candidates for the holon label include cells, organs, individual humans, household communities and full social-economic systems. Hierarchy theory (Ahl and Allen, 1996; Allen and Starr, 1982; Giampietro, 1994) further elaborated the concept of holarchies (hierarchy of holons), emphasizing a presumed hierarchical organization of complex adaptive systems.

The dual nature of a holon explains the systemic ambivalence found in the perception and representation of the elements of complex systems (Giampietro and Mayumi, 2018). Depending on the scale adopted, "an element" can be considered a structural whole (the local-scale view) or a functional part of a higher hierarchical level (the large-scale view). The large-scale view defines a relevant functional type. The local-scale, for cons, defines a pertinent structural type. The concept of metabolic processor represents a solution to deal with this epistemological predicament describing the characteristics of both structural and functional types. When implementing relational analysis we can use the four Aristotelian causes (Rosen, 1985, 1977) as a powerful semantic tool to identify relations over structural and functional elements and properly scale quantitative information across levels and scales. The final and efficient causes refer to the functionality of the element for the preservation of the identity of the network to which it belongs (what and why you do something and how in a relational network: the ontological, teleological and relational predicaments). On the contrary, the formal and material causes refer to the realization of structural elements expressing a function (how the purposes are realized, the procedural and practical predicaments). According to their formal and material cause metabolic components fill a given position in the network and are able to process a certain set of inputs and deliver a certain set of outputs at the speed expected by the rest of the network (Giampietro et al., 2006).

The concept of holon acknowledges the impossibility of having a substantive one-to-one mapping between types of organized structures and types of functional relations (Giampietro and Mayumi, 2018). A functional type can map onto different structural types and a structural type can have different functions. Besides, types are notional entities and cannot express agency. Agency can only be realized by an instance, a specific realization of the combination of the two types. In this sense, when representing the elements of complex systems we think on ideal types (e.g. the farm, the factory, the car). However, we can only observe special instances of these known typologies (e.g. a specific farm, factory or car). In relation to this problem by using grammars, i.e. expected relations over different types of metabolic processors of structural and functional types (Giampietro et al., 2012), it becomes possible to generate redundancy in the information space — as in the popular "sudoku game" (Giampietro and Bukkens, 2015). That is, we can triangulate expected values of structural and functional types (determined by benchmarks) against experienced values (derived from direct measurements or statistical data) and then contrast these expected relations against the observed characteristics of the activity of instances of metabolic elements.

In conclusion, the concept of holon and holarchies allows to handle the coexistence of multiple relevant scales and the use of different narratives. Within MuSIASEM social-economic systems are considered holarchies, metabolic networks where there is a tension between *downward causation* (Flack, 2017) , i.e. what is required by the functional relations over constituent components (according to the final and efficient causes associated with their notional representation) and *upward causation*, i.e. what can be supplied by local combinations of production processes given the constraints determined by technical viability and biophysical feasibility (according to the formal and material causes constraining tangible realizations). To deal with this issue MuSIASEM adopts two complementary views when analyzing metabolic requirements: (i) a top-down approach which is a relational analysis of notional entities (analysis of functions — final causes — expressed by functional types — efficient causes); and (ii) a bottom-up approach which is an analysis based on observed characteristics of instances (determined by the material cause) of structural types (determined by the formal cause). This double characterization permits to confront large-scale assessments based on aggregate statistics with local-scale assessments based on technical coefficients ensuring the robustness of the analysis (Giampietro et al., 2014).

3.4. The semiotic process.

Human societies not only exchange materials and energy with their environment but also information. Their forced metabolism entails a continuous change of environmental conditions. In order to continuously adjusting their state-pressure relations human societies must be anticipatory systems (Rosen, 1985) and must use models of its interaction with the context to guide action, learn and adapt. The production of scientific knowledge is key when generating anticipation. However, the process of scientific advice is embedded in a wider process that defines the identity and priorities to be solved by society as a whole: this is the semiotic process (Giampietro, 2019b).

Whereas simple physical systems may be well understood as simply behaving in a thermodynamic fashion, we cannot understand biosocial systems without invoking meaning and significance (Barbieri, 2019; Emmeche and Kull, 2011; Giampietro et al., 2006; Giampietro and Renner, 2020; Kull et al., 2009). All living systems are cognitive systems that validate the usefulness of their models through a process of interaction with the external world based on self-regulation from feedback (Capra, 1996). Relevant perceptions of the external world (semantics) are translated into a given representation (syntactic) to guide action (pragmatics). Results are evaluated against the expected outcome predicted by the model. If the living system has been successful in achieving its goals, then knowledge is validated. If not, new explanatory models must be generated until what Pattee (1995) calls "semantic closure" when all the steps between semantics, syntactic and pragmatics are coherent for the final responsible of evaluating the process.

In the particular case of human societies, achieve semantic closure is an intricate process, especially in sustainability issues where different agents, using non-equivalent criteria, have different goals and different perceptions and representations of what should be considered relevant and pertinent. In this sense, four components can be identified in the semiotic process of human societies: (i) scientific inquiry providing the representations; (ii) governance, providing the interpretations; (iii) social practices, giving the feed-back from the pragmatic step; and (iv) a political process defining the identity and determining the priorities over the problems to be solved by society as a whole (Giampietro, 2019b). The semiotic process reveals the fact that value systems, as a part of creating meaning, remain social and cannot be imputed to the organism themselves without resorting to problems of communicability. Due to the existence of power asymmetry in the political process it is important to avoid a hegemonization of particular perspectives and agendas in the political process in relation to the problems to be solved. A definition of concerns to be addressed too narrow, focused on a limited set of narratives and reflecting only the interest of a limited group of social actors can lead to "hypocognition" (Lakoff, 2010) i.e. a simplistic framing leaving out important aspects to be considered. This is especially relevant in the current circumstances where the development of modern orthodox economic narratives has hegemonized the structuring of the process of decision making.

The semiotic process has profound implications when using MuSiASEM. Humans represent in their scientific analysis only a shared perception of reality, not the actual reality (Giampietro, 2003). When providing scientific evidence to guide policy, we have to take into account which perspective is considered. There is an observer's point of view that must be integrated into the knowledge process. The selection of models, data and monitoring that result in facts to guide specific actions useful for society, are the result of the original choice about what narrative to use and what relevant concern to address. However, the priority given to different concerns (e.g. aspiration for economic growth or the need to preserve the environment) cannot be "scientifically justified". It simply reflects a normative decision, product of a particular political process. Consideration of the existence of different observers, especially when modelers are part of the system, and a semiotic process which is not external to power relations, turns MuSIASEM into a post-positivists approach that recognized the relevance of semiotics and values in the production of knowledge. Therefore, MuSIASEM takes into consideration the unavoidable existence of incommensurability of values, one of the foundations stones of EE (Martinez-Alier et al., 1998).

Finally, the idea of the existence of a semiotic process direct us towards the social and cultural causes of environmental deterioration, and therefore, towards the desirability of a metabolic pattern. The set of social practices that guarantee a certain social reproduction are the product of the semiotic process, i.e. a political process defining the identity and relevant problems to be solved. The semiotic process in modern societies is dominated by economic narratives under a framework of capital accumulation. It promotes an irrational belief in perpetual economic growth that clashes with the natural patterns established in the biosphere through which the planet balances and regulates itself. In turn, it generates a structural condition, a routine of accumulating capital, of making money, of frenetically producing goods for sale ignoring any kind of biophysical reality. So, the problem is not about an ontological entity (e.g. excessive GHG) but about a system that promotes unsustainable practices determined by the specific result of the semiotic process that answers questions like: "who are we as society?", "what are our goals?", "are we sovereign consumers or interdependent and ecodependent beings?".

3.6. Dynamic Energy Budget.

Herbert Spencer, one of the founding fathers of social science, correlated societal progress and energy surplus (McKinnon, 2010). The latter enabled social growth and thereby social differentiation. It, also, provided room for cultural activities beyond basic vital needs. Other eminent scholars as, Lotka (1922), Zipf (1949, 1941) and White (1943) have developed this idea from different fields. In this sense, the central idea of dynamic energy budget in MuSIASEM is that any metabolic system, as a social-economic system, has to invest energy in getting energy but at the same time has to invest energy in expressing other behavior such as maintaining and updating social institutions.

The concept of dynamic energy budget for the study of social-economic systems is based on previous works in the field of system ecology. Analyzing ecosystem structures, Ulanowicz (1986) found that the network of matter and energy flows conforming an ecosystem can be divided in two functional parts: the hypercycle and the dissipative part. The first part has to provide the required supply of energy (after considering local expenditure) to the rest of the system. The second has a pure dissipative nature and expresses activities that are net energy degraders. These two parts can be easily related to the two sides of a metabolic process: (i) the catabolic part (the one generating the hypercycle by destroying favorable gradients found in nature); and (ii) the anabolic part (the one expressing the activity of reproduction and control).

Following this conceptual distinction, the various functional compartments of a social-economic system can be divided between dissipative sectors, i.e. sectors involved in the metabolism of biophysical flows and use of exosomatic devices, without producing either of them (e.g. service, government and the household sectors); and hypercyclic sectors, i.e. sectors which output more biophysical flows and/or exosomatic devices that they use for their own metabolism (e.g agricultural, energy, mining and industrial sectors). The strength of the hypercycle part, defined as the level of biophysical surplus generated per unit of human activity, determines the size and the differentiation of activities that society can afford in the dissipative part. That is, there must be a balance between the energy and materials required to express the various societal functions and the supplied flow generated by the hypercycle part. This implies a forced relation between what is achieved (a material standard of living and key functions to be expressed) and what is expected (a supplied flow of energy and materials generated by the hypercyclic compartments) or, in other words, the characteristics of the production side and the consumption side do affect each other in an impredicative way. MuSIASEM accounts of fund and flow variables when characterizing the metabolic identity of human societies implies that both variables act as constraints in the viability of the dynamic equilibrium. The concept not only determines an entanglement over flows elements (e.g. energy, water and food) but also a dynamic equilibrium between requirement and supply of human time, power capacity and land use to produce and consume goods and services, supporting an idea of "strong sustainability" (Couix, 2019).

The internal balance between the hypercycle and the dissipative parts is useful to understand complexity. Complexity in human social systems can be defined as the ability of generating, maintaining and adapting a differentiation in both structure and behavior (Tainter, 1988). Complexity is associated with an enlargement of the dissipative part that requires a greater consumption of resources and, in parallel, powerful hypercyclic sectors processing all those resources. It is important to remark that today complexity is achieved mainly through the massive use of fossil and nuclear fuels. Because of them, the required level of productivity of production factors in contemporary developed societies (flows per hour of labor and per hectare of land use in the hypercycle part) is order of magnitude larger than the pace and density supply and sink capacity of natural processes. These high yields are the result of moving from systems based on circular flow-funds (input produced and wastes absorbed by ecological funds) to almost complete dependence on linear stock flows (inputs extracted from stocks and wastes overwhelming sink capacity) under a general framework of externalization and globalization (Giampietro, 2019a; Renner et al., 2020b).

This has made it possible to express structures and functions (in the dissipative part) that would otherwise not be possible.

4. Strengths and weaknesses of MuSIAEM

As we have discussed, MuSIASEM builds on a theoretical corpus developed for different purposes trying to connect and interrelate relevant aspects of SES. Conscious of the difficulty of this challenge MuSIASEM raises a biophysical post-positivist approach that, even seeking for quantitative analysis, it recognizes the relevance of semiotics and values in the production of knowledge. This make the method epistemologically and ontologically flexible and the problems that one can find are basically associated with their performance: it demands a lot of data and relies on data not always available or adequately organized (answering new scientific questions cannot be done by using data collected in relation to old questions). Practical aspects related to the implementation of MuSIASEM are not always well understood, especially when MuSIASEM is used in specific applications. This has generated the criticism that the method became quickly a-historical by relying on not standardized data (Gerber and Scheidel, 2018). This criticism is certainly true when assuming that MuSIASEM analysis provides substantive data comparable with data obtained by other "monoscale" protocols of accounting. However, this is not the case if we consider MuSIASEM as an approach studying patterns of relations over data that are defined across different levels of analysis. This is the case in historical metabolic analysis based on the study of exosomatic energy metabolic rates (Diaz-Maurin et al., 2018; Iorgulescu and Polimeni, 2009), economic job productivity (Sorman and Giampietro, 2011; Velasco-Fernández et al., 2015), demographical aspects (Giampietro et al., 2012), power capacity (Renner and Giampietro, 2020) or human activity allocation patterns (Velasco-Fernández et al., 2020b), all based in systematized data collected by statistical offices but interpreted and related in a different way.

Sustainability problems present a challenge to modern science. The successful development of new technologies and methods has made possible an incredible scientific and technical specialization bringing new insights and control to society. This success was based on the strategy of framing a problem at the time focusing on a specific manageable set of factors to be considered. This successful strategy has neglected more holistic and systemic perspectives required for handling sustainability issues, which became more and more difficult to cover due to the huge amount of specific knowledge, it is, specific known and unknown knowns to be considered. Sustainability problems are systemic and global by definition (e.g. biodiversity lost, global warming, stock depletion, sink saturation), and this integrated analysis has to include the functioning of societies, the functioning of ecosystems in which they are embedded and the implications of their interactions. Here is where MuSIASEM presents its strengths connecting: (i) levels (e.g. local, regional or national policies); (ii) scales (e.g. time and space effects of local optimizations as Jevons paradox or pressure externalization); and dimensions (e.g. energy, water, materials, human time, land use); with global sustainability problems, with the big picture.

Systemic traditional modeling tries to capture details and define concrete causal relationships to generate expected scenarios, something that governments and companies demand to orient and justify their planning and investment decisions. MuSIASEM can be used to generate scenarios and explore the option space, but normally works the other way around: an expected future is defined, and its plausibility is checked using identified technical benchmarks, social practices, metabolic patterns and relations (holarchies, hypercycles and openness) – what has been called *Quantitative Story Telling* (Giampietro, 2019b; Saltelli and Giampietro, 2017). This holistic view, allowing the avoidance of irrelevant details, is a strength in a context of high uncertainty, ignorance, indeterminacy and risks, where it is crucial to identify and discuss about them in extended-peer communities: *What we want to sustain? Which priorities and vulnerabilities are relevant? How precaution, prevention and mitigation should be considered?* However, this could be a weakness when dealing with issues in which we can define with high certainty the nature of the problems, the possible outcomes of choice, and where the moral values justifying the choice are uncontested. Unfortunately, this situation is pretty rare in sustainability science. Moreover, identify metabolic patterns and relations is not a straightforward issue, as it requires developing biophysical accounting and complexity analyses escaping the tradition of reductionism.

Critical aspects of complex systems as the consideration of multiple dimensions and scales and holarchies relations became crucial to identify the impredicative and side effects aspects that MuSIASEM looks to capture. In fact, MuSIASEM obsession for characterizing the trade-offs and winner-loser relations across levels, scales and dimensions is at the same time the major strengths and weakness of the method. Forcing to face uncertainty and transparency is a scientific value that is not always appreciated by societies that expect from science to get certainties and solutions more than new dilemmas. In relation to this point, MuSIASEM can contribute to increase trust in institutions moving to more democratic and transparent ways of government (from here its synergies with postnormal science, science and technology studies (STS) or multicriteria analysis (Giampietro and Funtowicz, 2020; Saltelli et al., 2020). In our view, society should value this aspect and consider it as a strength and not a weakness. Policy makers ask for certainties and "scientific evidences" that justify their decisions and actions. A method that continuously asks for reopening debates and re-politicizing the framing of critical issues certainly requires more time and efforts and makes more transparent the differences in relation to the interests and power of the different actors. In that sense, MuSIASEM builds on biosemiotics to recognize the key importance of validation of useful knowledge and human reflexivity on sustainability debates: *"meaning and beliefs are as important as material constraints to determine the feasibility of patterns of behavior"* (Giampietro et al., 2012, p. 72). Now that the MuSIASEM approach is becoming more mature, latest applications are making more explicit this critical semiotics aspects presenting the results as uncomfortable knowledge (see the Uncomfortable Knowledge Hub - uncomfortableknowledge.com).

5. Final considerations.

The most complex challenges facing humanity in the XXI century, including climate change, biodiversity loss and peak oil, reveal the existence of external biophysical limits. These limits (together with remaining poverty and inequality) do affect the stability of the economic process or in other words, the feasibility, viability and desirability off the metabolic pattern of social-economic systems. Dealing with these limits will require a total reconfiguration of our current pattern of material and energy use, a radical change in socio-economic institutions and a re-adjustment of current social practices. Despite of the urgency of this need, most institutions and citizenry remain in denial. The presence dominance of OE narrative filters out this uncomfortable knowledge. Therefore, the current unsustainability of the existing pattern of economic development is not discussed because it represents a threat to the stability of hegemonic institutions. However, if one admits the existence of biophysical limits and the impossibility of maintaining the standard of living promised by consumerism that cannot be guaranteed to the growing world population, new narratives and perceptions are necessary in order to be able to envision other societal configurations. This fact translates into the need of new epistemic tools capable of: (i) informing this deliberative process by providing insights over the pros and cons of different narratives; and (ii) flagging the implausibility of many delusional technoscientific imaginaries.

In this article the MuSIASEM methodology has been discussed to provide a coherent analysis of the biophysical factors determining the sustainability of social-economic systems. The method provides an alternative framing of analysis capable of integrating the consideration of different aspects relevant for the discussion over sustainability. It facilitates a diagnostic of the material and energy requirements necessary for the maintenance and reproduction of social-economic systems. In addition, MuSIASEM can be used in anticipation mode in the discussion about possible scenarios determining the option space to more sustainable states. In this sense MuSIASEM, being faithful to the original principles of EE (e.g. consideration of a social-economic system as a SES, incommensurability of values, use of indicators belonging to different dimensions, strong sustainability) can be an excellent candidate to support the ambitious founding plan of EE.

Although MuSIASEM is an eminently quantitative tool, its theoretical foundations invite us to reflect on the fact that crunching more and more numbers within a given definition of identity of a SES will not provide new solutions to sustainability issues. In a world where all the parts of the system are connected, the ecological dilemma may be simple the result of doing too much. That's why the sustainability of human systems seems to require a subtle balance between efficiency — i.e. doing better according to what is known — and adaptability — i.e. changing the identity of the system in the face of changes in boundary conditions. In other words, it is not always the external world that has to be adjusted according to our wants. We have also to learn how to adjust our wants to the constraints provided by the external world (as it was done in ancient cultures, before the intoxication of produced by OE). This entails to look reflexively at the way we carry out our particular semiotic process defining our identity, the narratives to be used and the relevant aspects to be considered. With this in mind, we should be skeptical with excessive optimistic postures regarding the unilateral use of technological innovations to solve sustainability problems.

In fact, sustainability solutions do not exist. They must be created and nurtured in a political process. In this process, biophysical constraints affect the option space. If, as Tanuro (2020) states, there is no liberty without awareness of the limits, MuSIASEM could represent for those seriously concerned with the future of our society the kind of special sunglasses described in the movie of Carpenter, to be used to get better perceptions and representations of our sustainability predicament and for the discussion of radical imaginaries of change.

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References

Ahl, V., Allen, T.F.H., 1996. Hierarchy Theory. Columbia University Press, New York.

Allen, T.F.H., Starr, T., 1982. Hierarchy: Perspectives for Ecological Complexity. University of Chicago Press, Chicago.

Ashukem, J.C.N., 2020. The SDGs and the bio-economy: fostering land-grabbing in Africa. Rev. Afr. Polit. Econ. 0, 1–16. https://doi.org/10.1080/03056244.2019.1687086

Barbieri, M., 2019. Code Biology, Peircean Biosemiotics, and Rosen's Relational Biology. Biol. Theory 14, 21–29. https://doi.org/10.1007/s13752-018-0312-z.

Berkes, F., Colding, J., Folke, C., 2003. Navigating Social-Ecological Systems : Building Resilience for Complexity and Change. Columbia University Press, New York.

Cadillo-Benalcazar, J.J., Giampietro, M., Bukkens, S.G.F., Strand, R., 2020a. Multi-scale integrated evaluation of the sustainability of large-scale use of alternative feeds in salmon aquaculture. J. Clean. Prod. 248, 119211. https://doi.org/10.1016/j.clepro.2019.119210

Cadillo-Benalcazar, J.J., Renner, A., Giampietro, M., 2020b. A multiscale integrated analysis of the factors characterizing the sustainability of food systems in Europe. J. Environ. Manage. 271, 110944. https://doi.org/10.1016/j.jenvman.2020.110944

Capra, F., 1996. The Web of Life: A New Synthesis of Mind and Matter. HarperCollins, London.

Carpenter, J., 1988. They live. Universal Pictures, USA.

Cilliers, P., 1998. Complexity and postmodernism: Understanding complex systems. Routledge, London.

Couix, Q., 2019. Natural resources in the theory of production: the Georgescu-Roegen/Daly versus Solow/Stiglitz controversity. Eur. J. Hist. Econ. Thought 26, 1341–1378. https://doi.org/10.1080/09672567.2019.1679210

Couix, Q., 2018. From Methodology to Practice (and Back): Georgescu-Roegen's Philosophy of Economics and the Flow-Fund Model. halshs-01854031 [WWW Document] URL https://halshs.archives-ouvertes.fr/halshs-01854031.

Daly, H., 2019a. Growthism: its ecological, economic and ethical limits. Real-World Econ. Rev. 87, 9-22 Available on line: http://www.paecon.net/PAEReview/issue87/Daly87.pdf

Daly, H., 2019b. Some overlaps between the first and second thirty years of ecological economics. Ecol. Econ. 164, 106372. https://doi.org/10.1016/j.ecolecon.2019.106372

Daly, H., 2005. Economics in a full world. Sci. Am. 293, 78–85.

Diaz-Maurin, F., Chiguvare, Z., Gope, G., 2018. Scarcity in abundance: The challenges of promoting energy access in the Southern African region. Energy Policy 120, 110–120. https://doi.org/10.1016/j.enpol.2018.05.023

Emmeche, C., Kull, K. (eds. ., 2011. Towards a Semiotic Biology: Life is the Action of Signs. Imperial College Press, London.

Fiorito, G., 2013. Can we use the energy intensity indicator to study “decoupling” in modern economies? J. Clean. Prod. 47, 465–473. https://doi.org/10.1016/j.jclepro.2012.12.031

Flack, J.C., 2017. Coarse-graining as a downward causation mechanism Subject Areas : Author for correspondence : Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 375, 20160338.

Funtowicz, S., Ravetz, J., 1993. Science for the post-normal age. Futures 25, 735–755.

Gell-Mann, M., 1994. The Quark and the Jaguar. Freeman, New York.

Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process. Harvard University Press, Cambridge.

Gerber, J.F., Scheidel, A., 2018. In Search of Substantive Economics: Comparing Today’s Two Major Socio-metabolic Approaches to the Economy – MEFA and MuSIASEM. Ecol. Econ. 144, 186–194. https://doi.org/10.1016/j.ecolecon.2017.08.012

Giampietro, M., 2019a. On the Circular Bioeconomy and Decoupling: Implications for Sustainable Growth. Ecol. Econ. 162, 143–156. https://doi.org/10.1016/j.ecolecon.2019.05.001.

Giampietro, M., 2019b. The quality of scientific advice for policy: a few insights from complexity. Report produced in the context of the Horizon2020 project MAGIC, Grant Agreement No. 689669, 07 May 2019. Available on line: https://magic-nexus.eu/documents/quality-scientific-advice-policy-insights-complexity

Giampietro, M., 2003. Multi-Scale Integrated Analysis of Agro-ecosystems. CRC Press, Boca Raton.

Giampietro, M., 1994. Using hierarchy theory to explore the concept of sustainable development. Futures 26, 616–625. https://doi.org/10.1016/0016-3287(94)90033-7

Giampietro, M., Allen, T.F.H., Mayumi, K., 2006. The epistemological predicament associated with purposive quantitative analysis. Ecol. Complex. 3, 307–327. https://doi.org/10.1016/j.ecocom.2007.02.005.

Giampietro, M., Aspinall, R.J., Ramos-Martín, J., Bukkens, S.G.F., 2014. Resource Accounting for Sustainability Assessment: The Nexus between Energy, Food, Water and Land use. Routledge, London.

Giampietro, M., Bukkens, S.G.F., 2015. Analogy between Sudoku and the multi-scale integrated analysis of societal metabolism. Ecol. Inform. 26, 18–28. https://doi.org/10.1016/j.ecoinf.2014.07.007

Giampietro, M., Cadillo-Benalcazar, J.J., Di Felice, L.J., Manfroni, M., Pérez-Sánchez, L., Renner, A., Ripa, M., Velasco-Fernández, R., Bukkens, S.G.F., 2020. Report on the Experience of Applications of the Nexus Structuring Space in Quantitative Storytelling. MAGIC (H2020–GA 689669) Project Deliverable 4.4, 30 August 2020. Available on line: https://magic-nexus.eu/sites/default/files/files_documents_repository/d4.4_nexus-structuring-space_30-08-2020.pdf

Giampietro, M., Funtowicz, S., 2020. From elite folk science to the policy legend of circular economy. Environ. Sci. Policy 109, 64–72. https://doi.org/10.1016/j.envsci.2020.04.012

Giampietro, M., Mayumi, K., 2018. Unraveling the complexity of the Jevons Paradox: The link between innovation, efficiency, and sustainability. Front. Energy Res. 6, 1–13. https://doi.org/10.3389/fenrg.2018.00026

Giampietro, M., Mayumi, K., 2010. Multi-Scale Integrated Assessment of Societal Metabolism: introducing the approach. Popul. Environ. 22, 109–153.

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

Giampietro, M., Mayumi, K., Şorman, A.H., 2013. Energy Analysis for a Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism. Routledge, London. https://doi.org/10.4324/9780203107997

Giampietro, M., Renner, A., 2020. The Generation of Meaning and preservation of Identity in Complex Adaptive Systems-The LIPHE4 Criteria, in: Braha, D., et al. (Ed.), Unifying Themes in Complex Systems X: Proceedings of the Tenth International Conference on Complex Systems. Springer (Series: Springer Proceedings in Complexity), Cham, Switzerland.

González-López, R., Giampietro, M., 2018. Relational analysis of the oil and gas sector of Mexico: Implications for Mexico's energy reform. Energy 154, 403–414. https://doi.org/10.1016/j.energy.2018.04.134

González-López, R., Giampietro, M., 2017. Multi-scale integrated analysis of charcoal production in complex social-ecological systems. Front. Environ. Sci. 5:54. https://doi.org/10.3389/fenvs.2017.00054

González de Molina, M., Soto Fernández, D., G., G.C., Infante Amate, J., Aguilera Fernández, E., Vila Traver, R., García Ruiz, R., 2019. Historia de la agricultura española desde una perspectiva biofísica 1900-2010. Gobierno de España. Ministerio de Agricultura, Pesca y Alimentación, Madrid.

González de Molina, M., Toledo, V.M., 2014. The Social Metabolism. A Socio-Ecological Theory of Historical Change. Springer International Publishing, Berlin. https://doi.org/10.4324/9781315679747-14

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Contributions of sociometabolic research to sustainability science. Nat. Sustain. 2, 173–184. https://doi.org/10.1038/s41893-019-0225-2

Hagens, N.J., 2020. Economics for the future - Beyond the superorganism. Ecol. Econ. 169, 16. https://doi.org/10.1016/j.ecolecon.2019.106520.

Holland, J.H., 2006. Studying complex adaptive systems. J. Syst. Sci. Complex 19, 1–8. https://doi.org/10.1007/s11424-006-0001-z

Holland, J.H., 1995. Hidden Order: How Adaptation Builds Complexity. Perseus Books, New York,NY.

Holling, C.S., 2001. Understanding the complexity of economic, ecological, and social systems. Ecosystems 4, 390–405. https://doi.org/10.1007/s10021-001-0101-5.

Iorgulescu, R.I., Polimeni, J.M., 2009. A multi-scale integrated analysis of the energy use in Romania, Bulgaria, Poland and Hungary. Energy 34, 341–347. https://doi.org/10.1016/j.energy.2008.09.003

IPBES, 2019. Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystems Services [WWW Document] IPBES. URL https://ipbes.net/global-assessment-report-biodiversity-ecosystem-services. (accessed 5.20.20)

Koestler, A., 1967. The Ghost in the Machine. Macmillan Co., New York.

Kull, K., Deacon, T., Emmeche, C., Hoffmeyer, J., Stjernfelt, F., 2009. Theses on biosemiotics: Prolegomena to a theoretical biology. Biol. Theory 4, 167–173. https://doi.org/10.1162/biot.2009.4.2.167

Lakoff, G., 2010. Why it matters how we frame the environment. Environ. Commun. A J. Nat. Cult. 4, 70–81. https://doi.org/10.1080/17524030903529749.

Lotka, A.J., 1922. Contribution to the energetics of evolution. Proc. Natl. Acad. Sci. 8, 147–151. https://doi.org/10.1073/pnas.8.6.147.

Louie, H.A., 2017. Intangible Life: Functional Connections In Relational Biology. Springer International, Cham.

Luhmann, N., 1995. Social Systems. Stanford University Press, Stanford.

Macy, J., Johnstone, C., 2012. Active Hope: How We Face the Mess We're Without Going Crazy. New World Library, Novato, California.

Martinez-Alier, J., Munda, G., O'Neill, J., 1998. Weak comparability of values as a foundation for Ecological Economics. Ecol. Econ. 26, 277–286.

Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., 2018. Special Report on Global Warming of 1.5^{o} C.

McKinnon, A., 2010. Energy and society: Herbert Spencer's "energetic sociology" of social evolution and beyond. J. Class. Sociol. 10, 439–455. https://doi.org/10.1177/1468795X10385184.

Melgar-Melgar, R.E., Hall, C.A.S., 2020. Why ecological economics needs to return to its roots: The biophysical foundation of socio-economic systems. Ecol. Econ. 169, 106567. https://doi.org/10.1016/j.ecolecon.2019.106567

Munda, G., 2008. Social Multi-Criteria Evaluation for a Sustainable Economy. Springer, Berlin.

Naredo, J.M., 2015. La Economía en Evolución : Historia y Perspectivas de las Categorías Básicas del Pensamiento Económico (4^{a}ed.). Siglo XXI, Madrid.

Odum, H.T., 1971. Environment, Power and Society. Wiley-Interscience, New York.

Parra, R., Bukkens, S.G.F., Giampietro, M., 2020. Exploration of the environmental implications of ageing conventional oil reserves with relational analysis. Sci. Total Environ. 749, 14237. https://doi.org/10.1016/j.scitotenv.2020.142371

Parra, R., Di Felice, L.J., Giampietro, M., Ramos-Martín, J., 2018. The metabolism of oil extraction: A bottom-up approach applied to the case of Ecuador. Energy Policy 122, 63–74. https://doi.org/10.1016/j.enpol.2018.07.017

Pattee, H.H., 1995. Evolving self-reference: Matter, symbols and semantic closure. Commun. Cogn. Intell. 12, 9–27.

Pérez-Sánchez, L., Velasco-Fernández, R., Giampietro, M., 2020. The international division of labor and embodied working time in trade for the US, the EU and China. Ecol. Econ. 106909. https://doi.org/10.1016/j.ecolecon.2020.106909

Pirgmaier, E., Steinberger, J.K., 2019. Roots, riots and radical change-a road less travelled for ecological economics. Sustainability 11. https://doi.org/10.3390/su11072001

Prigogine, I., Glansdorff, P., 1971. Thermodynamic Theory of Structure, Stability and Fluctuation. Wiley, New York.

Prigogine, I., Nicolis, G., 1977. Self-Organization in Nonequillibrium Systems. Wiley, New York.

Rashevsky, N., 1935. Mathematical Biophysics. Nature 135, 528–530. https://doi.org/10.1038/135528a0

Rayner, S., 2012. Uncomfortable knowledge: the social construction of ignorance in science and environmental policy discourses. Econ. Soc. 41, 107–125. https://doi.org/10.1080/03085147.2011.637335.

Renner, A., Cadillo-Benalcazar, J.J., Benini, L., Giampietro, M., 2020a. Environmental pressure of the European agricultural system: Anticipating the biophysical consequences of internalization. Ecosyst. Serv. 46, 101195. https://doi.org/10.1016/j.ecoser.2020.101195

Renner, A., Giampietro, M., 2020. Socio-technical discourses of European electricity decarbonization: Contesting narrative credibility and legitimacy with quantitative story-telling. Energy Res. Soc. Sci. 59, 101279. https://doi.org/10.1016/j.erss.2019.101279

Renner, A., Louie, H.A., Giampietro, M., 2020b. Cyborgization of Modern Social-Economic Systems: Accounting for Changes in Metabolic Identity., in: Braha, D., et al. (Ed.), Unifying Themes in Complex Systems X: Proceedings of the Tenth International Conference on Complex Systems. Springer (Series: Springer Proceedings in Complexity), Cham, Switzerland.

Riechmann, J., 2017. ¿Vivir como buenos huerfanos? Ensayos sobre el sentido de la vida en el Siglo de la Gran Prueba. Los Libros de la Catarata, Madrid.

Ripa, M., Di Felice, L.J., Giampietro, M., 2021. The energy metabolism of post-industrial economies. A framework to account for externalization across scales. Energy 214, 118943. https://doi.org/10.1016/j.energy.2020.118943

Rittel, H.W., Webber, M.M., 1973. Dilemmas in a general theory of planning. Policy Sci. 4, 155–169. https://doi.org/10.1007/BF01405730

Ropke, I., 2005. Trends in de development of ecological economics from the late 1980s to the erarly 2000s. Ecol. Econ. 55, 262–290.

Ropke, I., 2004. The early history of modern ecological economics. Ecol. Econ. 50, 293–314.

Rosen, R., 2005. Life Itself: A Comprehensive Inquiry into the Nature, Origin, and Fabrication of Life. Columbia University Press, New York.

Rosen, R., 2000. Essays on Life Itself. Columbia University Press, New York.

Rosen, R., 1985. Anticipatory Systems: Phylosophical, Mathematical and Methodological Foundations. Pergamon Press, New York.

Rosen, R., 1977. Complexity as a system property. Int. J. Gen. Syst. 3, 227–232.

Saltelli, A., Benini, L., Funtowicz, S., Giampietro, M., Kaiser, M., Reinert, E., van der Sluijs, J., 2020. The technique is never neutral. How methodological choices condition the generation of narratives for sustainability. Environ. Sci. Policy 106, 87–98. https://doi.org/10.1016/j.envsci.2020.01.008

Saltelli, A., Giampietro, M., 2017. What is wrong with evidence based policy, and how can be improved? Futures 91, 62–71. https://doi.org/10.1016/j.futures.2016.11.012

Serrano-Tovar, T., Peñate Suárez, B., Musicki, A., de la Fuente Bencomo, J.A., Cabello, V., Giampietro, M., 2019. Structuring an integrated water-energy-food nexus assessment of a local wind energy desalination system for irrigation. Sci. Total Environ. 689, 945–957. https://doi.org/10.1016/j.scitotenv.20190.06.422

Simon, H.A., 1962. The Architecture of Complexity: Hierarchic Systems. Proc. Am. Philos. Soc. 106, 467–482. https://doi.org/10.2307/985254

Sorman, A.H., Giampietro, M., 2011. Generating better energy indicators: Addressing the existence of multiple scales and multiple dimensions. Ecol. Modell. 223, 41–53. https://doi.org/10.1016/j.ecolmodel.2011.10.014

Spash, C.L., 2020. A tale of three paradigms: Realising the revolutionary potential of ecological economics. Ecol. Econ. 169, 106518. https://doi.org/10.1016/j.ecolecon.2019.106518

Spash, C.L., Smith, T., 2019. Of ecosystems and economies:re-connecting economies with reality. Real-World Econ. Rev. 19, 221-229 Available on line: http://www.paecon.net/PAEReview/issue87/SpashSmith87.pdf

Steffen, W., Rockström, J., Richarson, K., Lenton, T.M., Folke, C., Liverman, D., Summerhayes, C.P., Barnosky, A.D., Cornell, S.E., Cricifix, M., Donges, J.F., Fetzer, I., Lade, S.J., Scheffer, M., Winkelmann, R., Schellnhube, H.J., 2018. Trajectories of the Earth System in the Anthropocene. PNAS 115, 8252–8259. https://doi.org/10.1073/pnas.1810141115

Tainter, J.A., 1988. The Collapse of Complex Societies. Cambridge University Press, Cambridge.

Tanuro, D., 2020. El ecosocialismo como imaginario. Nuevos paradigmas y estrategias frente al desastre, in: Vindel, J. (Ed.), Hacia Una Nueva Imaginación Ecosocial. Narrativas y Transiciones Ante La Crisis de Civilización. Talk in MACBA, Barcelona. Available on: https://www.macba.cat/es/exposiciones-actividades/actividades/hacia-nueva-imaginacion-ecosocial.

Ulanowicz, R.E., 1986. Growth and Development: Ecosystem Phenomenology. Springer-Verlag, New York.

UN Enviromemnt, 2019. Global Environment Outlook (GEO-6): Summary for Policymakers. Cambridge University Press, Nairobi. https://doi.org/10.1017/9781108639217

Velasco-Fernández, R., 2020. Depoliticizing and repolicizing SDGs., in: The MAGIC Consortium (Ed.), The Nexus Times. Megaloceros Press, Bergen. https://doi.org/10.24994/2020/nexustimes

Velasco-Fernández, R., 2017. The Pattern of Socio-Ecological Systems. A Focus on Energy, Human Activity, Value Added and Material Products. Universitat Autònoma de Barcelona (PhD Thesis).

Velasco-Fernández, R., Dunlop, T., Giampietro, M., 2020a. Fallacies of energy efficiency indicators: Recognizing the complexity of the metabolic pattern of the economy. Energy Policy 137. https://doi.org/10.1016/j.enpol.2019.111089

Velasco-Fernández, R., Giampietro, M., Bukkens, S.G.F., 2018. Analyzing the energy performance of manufacturing across levels using the end-use matrix. Energy 559–572. https://doi.org/10.1016/j.energy.2018.07.122

Velasco-Fernández, R., Pérez-Sánchez, L., Chen, L., Giampietro, M., 2020b. A becoming China and the assisted maturity of the EU: Assessing the factors determining their energy metabolic patterns. Energy Strateg. Rev. 32, 1000562. https://doi.org/10.1016/j.esr.2020.100562

Velasco-Fernández, R., Ramos-Martín, J., Giampietro, M., 2015. The energy metabolism of China and India between 1971 and 2010: Studying the bifurcation. Renew. Sustain. Energy Rev. 41, 1052–1066. https://doi.org/10.1016/j.rser.2014.08.065

Wallace, Rob, Liebman, A., Chaves, L.F., Wallace, Rodrick, 2020. COVID-19 and Circuits of Capital [WWW Document]. Mon. Rev. URL https://monthlyreview.org/2020/05/01/covid-19-and-circuits-of-capital/ (accessed 5.20.20).

White, L.A., 1943. Energy and evolution of culture. Am. Anthropol. 14, 335–356.

Zipf, G.K., 1949. Human Behaviour and the Principle of Least Effort: An Introduction to Human Ecology. Addison-Wesley, Cambridge.

Zipf, G.K., 1941. National Unity and Disunity: The Nation as a Biosocial Organism. Principia Press, Bloomington, IN.

Appendix 3-Numerical assumptions.

1. Human activity

1.1. Total Human Activity

The calculation about the equivalent population has been carried out from data available in (Departament de Medi Ambient, 2016a) using the following formula:

"Població equivalent"="resident" + (0,4*"fronterer") + ("temporer"*180/365) + (0,4*"excursionista"/365) + ("pernoctacions turistes"/365).

Taula 2.4 Evolució de la població equivalent

ANY	TIPUS DE CATEGORIA							POBLACIÓ EQUIVALENT
	Resident		Excursionista	Turista		Fronterer	Temporer	
	Població total censada	Població estimada		Turistes	Pernoctacions			
1999	65.971	-	7.074.765	2.347.001	0	0	0	-
2000	65.844	57.636	6.235.603	2.945.719	6.945.582	1.895	0	84.257
2001	66.334	58.065	5.856.117	3.516.261	7.077.629	2.061	0	84.698
2002	67.159	58.787	6.094.514	3.387.586	6.866.251	2.201	2.657	86.468
2003	72.320	63.305	6.429.986	3.137.738	6.025.441	2.307	2.575	89.052
2004	76.875	67.292	6.303.041	2.791.116	6.025.441	2.378	2.868	93.073
2005	78.549	68.757	5.943.038	2.418.409	6.604.984	2.386	2.905	95.753
2006	81.222	71.097	5.803.430	2.226.922	6.494.056	2.354	2.995	97.667
2007	83.137	72.773	5.865.942	2.189.421	7.033.956	2.305	3.333	101.038
2008	84.484	73.952	5.738.460	2.059.451	6.478.548	2.135	3.300	100.472
2009	84.082	73.600	5.707.010	1.829.869	5.682.729	1.907	2.906	97.619
2010	85.015	70.290	5.677.343	1.808.001	6.460.842	1.797	3.168	96.494
2011	78.115	69.772	5.741.317	1.818.989	6.514.859	1.721	2.966	96.064
2012	76.246	69.758	5.662.501	2.237.939	6.636.279	1.642	2.778	96.172
2013	76.098	69.966	5.348.108	2.328.124	6.975.867	1.568	2.963	97.027
2014	76.949	70.570	5.433.334	2.363.436	6.780.065	1.494	3.213	97.282
2015	78.014	71.732	5.180.708	2.670.444	8.149.684	1.424	3.525	102.045

Revisió del Pla nacional de residus d'Andorra (PNR) 2017-2020 16

Font: Departament d'Estadística

Thus, THA="població equivalent"*8.760 hours/year.

1.2. HA in the PW sector

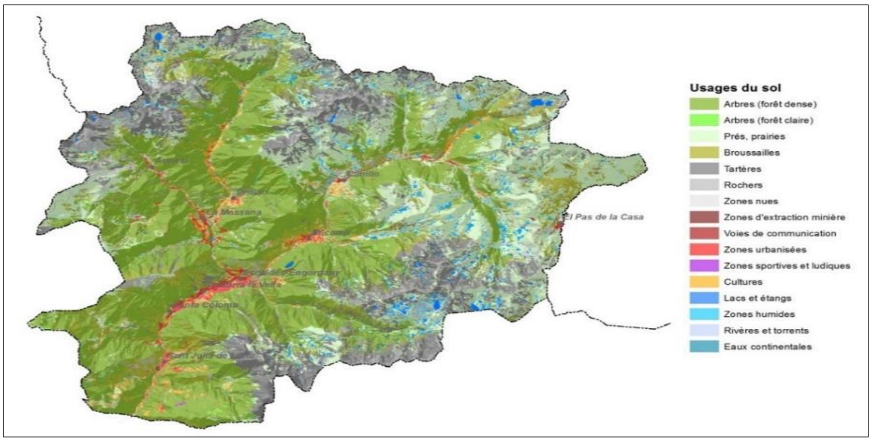
The aggregation of the economic subsectors in AG, ICM and SG sectors has been done from data in (Centre de Recerca Sociològica, 2018a) and considering the following grouping:

AG	A-Agricultura, ganadería, pesca y silvicultura B-Pesca
ICM	C-Industrias extractivas D-Industrias manufactureras E-Producción y distribución de energía eléctrica, gas y agua F-Construcción
SG	G-Comercio y reparación vehículos motor H-Hostelería I-Transportes y comunicaciones J-Sistema financiero K-Actividades inmobiliarias y servicios empresariales L-Administración pública y seguridad social M-Educación N-Actividades sanitarias y veterinarias, servicios sociales O-Otras actividades sociales y servicios personales P-Hogares que ocupan personal doméstico Q-organismos extraterritoriales T-Trabajos domésticos a la comunidad

Full-time contracts of 1.800 hours per year have been considered to calculate the hours of self-employed and employed workers. Moreover a amount of 345.284 extra hours in the SG sector has been included (6,6% "trabajadores hosteleria" + 3,6% "trabajadores comercio" + 4,5% "trabajadores servicios empresariales".

2. Land Use

Data about land use is only available in (CENMA-IEA, 2012b).



This source allows obtaining the following percentages:

Categoria	MCSA 1948 (%)	MCSA 1972 (%)	MCSA 1995 (%)	MCSA 2012 (%)	Diferència any 48-12 (%)	Increment (%)
Arbrat clar	3,28	1,62	0,81	0,42	-2,85	-87,1
Arbrat dens	29,43	33,01	38,23	40,36	10,93	37,1
Matollars	11,41	12,1	10,14	9,28	-2,13	-18,7
Prats i herbassars	29,20	29,18	26,21	25,04	-4,16	-14,2
Roquissars	6,83	5,69	5,68	6,84	0,01	0,1
Tarteres	11,25	12,9	14,09	12,96	1,71	15,2
Zones nues	0,09	0,36	1,02	0,85	0,76	892,6
Aigües continentals	0,37	0,41	0,41	0,43	0,06	16,6
Conreus	5,14	3,57	1,71	1,71	-3,43	-66,7
Zones urbanitzades	0,16	0,51	1,32	1,51	1,35	839,2
Vies de comunicació	0,18	0,22	0,35	0,58	0,41	229,6
Sense dades	2,66	0,51	0	0	-2,66	-100,0

Urbanized areas have been disaggregated based on (Departament d'Estadística, 2019a):

Espacio urbano:	1,71%
Superficie viviendas	59%
Superficie almacén	6%
Superficie despacho	2%
Superficie local comercial	6%
Superficie hotel	10%
Superficie otras edificaciones	17%

3. Energy Throughput

Data from calculating the requirements of the HH sector have been obtained from (Travesset-Baro, 2017), from the following assumptions:

Sector Residencial	2015
número unifamiliares	8,07%
número plurifamiliares	91,93%
Superficie (m^2) media plurifamiliares	83,46
Superficie media (m^2) unifamiliares	325,61
Superficie a calentar viviendas unifamiliares (m2)	122
Población	71732
Personas/vivienda	2,39
Estimación número de viviendas	30.013
Estimación viviendas unifamiliares	2.422
Estimación viviendas plurifamiliares	27.591
Estimación superficie viviendas unifamiliares a calentar (m^2)	295.494
Estimación superficie viviendas plurifamiliares a calentar (m2)	2.302.771

Moreover data about Fuel and Heat for the whole system can be found in the mentioned source with these numbers:

Fuel (Travesset 2017) GWh		
Turismos	571,63	44%
Transporte mercaderías	107,97	8%
Transporte pasajeros	25,79	2%
Motos	8,77	1%
Fuel turismo	583,37	45%
Total	1297,53	100%

Heat (Fuel doméstico) (Travesset 2017) GWh		
Residencial	168,67	32%
Sector secundario	9,7	2%
Terciario	285,08	55%
Administración pública	57,12	11%
Total	520,57	100%

Appendix 4-Provisional index for the doctoral thesis

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