MULTI-SCALE INTEGRATED ANALYSIS OF SOCIETAL AND ECOSYSTEM METABOLISM (MuSIASEM) REVISITED: SYNTHESIZING AND UPDATING THE THEORETICAL FOUNDATIONS

MULTI-SCALE INTEGRATED ANALYSIS OF SOCIETAL AND ECOSYSTEM METABOLISM (MuSIASEM) REVISADO: SÍNTESIS Y ACTUALIZACIÓN DE LOS FUNDAMENTOS TEÓRICOS

Juan Jesús Larrabeiti-Rodríguez
University of Andorra (UdA)
ORCID iD: https://orcid.org/0000-0001-5419-6780
jlarrabeiti@uda.ad

Raúl Velasco-Fernández
Institute of Environmental Science and Technology (ICTA)
Autonomous University of Barcelona (UAB)/University of Andorra (UdA)
ORCID iD: https://orcid.org/0000-0002-5438-1158
raul.Velasco@uab.cat

Fecha de recepción: 06.06.2022
Fecha de aceptacion: 29.11.2022

Abstract

Biophysical limits are becoming more evident now that the global economy has moved from an "empty world" to a "full world". Acknowledging these limits requires a total reconfiguration of our current material and energy use pattern and a re-adjustment of existing social practices. Currently, dominant narratives refuse to acknowledge this fact. However, the failures in the fight to avoid irreversible damage to the biosphere are exposing the nature of the crisis: urgent action is needed, but adequate perspectives and analytical tools are lacking. This paper highlights the relevance of Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), in its more mature version, to respond to these shortcomings by providing an analytical approach to sustainability based on complexity. To this end, the paper synthesizes the basic rationale of MuSIASEM, clarifying its interpretation of social-economic systems, the economic process and the sustainability predicament. The article also revisits and updates the robustness of its theoretical foundations, examining and discussing the concepts combined in the analytical framework. In addition, new analytical tools such as the metabolic processor, the externalized end-use matrix and the externalized environmental pressure matrix are introduced with reference to the latest case studies where they have been applied for an integrated and meaningful analysis of sustainability across dimensions, scales and levels. Finally, the paper concludes by noting that MuSIASEM is a methodology faithful to key principles of ecological economics.

Keywords: *MuSIASEM, theoretical foundations, analytical tools, sociometabolic research, sustainability.*

Resumen

La existencia de límites biofísicos es cada vez más evidente ahora que la economía global ha pasado de un "mundo vacío" a un "mundo lleno". Reconocer estos límites requiere una reconfiguración total de nuestro patrón de uso de materiales y energía y un reajuste de las actuales prácticas sociales. Actualmente, las narrativas dominantes evitan reconocer este desafío. Sin embargo, el fracaso en la lucha para evitar daños irreversibles a la biosfera está exponiendo la naturaleza de la crisis: se necesitan medidas urgentes, pero faltan perspectivas y herramientas analíticas adecuadas. El presente artículo destaca la relevancia de la metodología *Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)*, en su versión más madura, para responder a estas deficiencias proporcionando un enfoque analítico de la sostenibilidad basado en la complejidad. Con este fin, el documento sintetiza la racionalidad básica de la metodología, clarificando su interpretación de los sistemas socioeconómicos, el proceso económico y el dilema de la sostenibilidad. El artículo también revisa y actualiza la solidez de sus fundamentos teóricos, examinando y discutiendo los conceptos combinados en el marco analítico. Además, nuevas herramientas analíticas como el procesador metabólico, la matriz de usos finales externalizada y la matriz de presiones ambientales externalizada son introducidas haciendo referencia a los últimos estudios en los que se han aplicado para un análisis integrado y significativo de la sostenibilidad a través de diferentes dimensiones, escalas y niveles. Finalmente, el artículo concluye señalando que MuSIASEM es una metodología fiel a los principios clave de la economía ecológica.

Palabras clave: *MuSIASEM, fundamentos teóricos, herramientas analíticas, investigación sociometabólica, sostenibilidad.*

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 the aliens' plans. In fact, the movie points to a well-known subject in social theory: the existence of dominant imaginaries shaping what are the relevant aspects of reality that should be considered by a given society at the moment of deciding action (Jasanoff & Kim, 2015). The point to be made here is that the present prevalence 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 & Smith, 2019). Therefore, some hegemonic statements driving social-economic systems are based on optimization of processes, innovation and globalization through trade that seek always for more productivism without questioning economic growth (Spash, 2020), overconsumption (Wiedmann *et al.*, 2020) or the increasingly unequal distribution of wealth (Ahmed *et al.*, 2022).

According to Giampietro and Funtowicz (2020), the success of OE can be explained not because of its ability to provide insights about how to guide action in relation to the sustainability of modern societies, but rather because of its capacity to filter out uncomfortable knowledge that could destabilize the actual structure of power. Thus, the systemic application of OE's narratives keeps the sustainability debate depoliticized

(Di Felice *et al.*, 2021) and allows one to envision the future as if the "business as usual" state is the best possible in which society is "saved" by smart technologies and innovative business models. This is why OE's narratives have to be embedded in policy legends like the circular economy, zero-emissions or zero-waste processes, decoupling or green growth (Giampietro & Funtowicz, 2020). Consequently, a constant "social construction of ignorance" subjected to the systemic exclusion of "uncomfortable knowledge" (Rayner, 2012) is produced, removing from sustainability discussions robust knowledge claims that point out cost-shifting practices, critical tensions between material standards of living and ecological damage or resource stock depletion, among others. In this way, the biophysical challenges determined by the fact that the global economy has moved from operating in an empty world to a full world (Daly, 2005) can be systematically ignored.

This paper discusses how Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) (Giampietro & Mayumi, 2000a, 2000b) helps transform existing perceptions and representations of society-nature relations into a more holistic one which accounts for the existence of biophysical limits. MuSIASEM is an accounting scheme 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. MuSIASEM is one of the main methodological approaches found in sociometabolic studies (González de Molina *et al.*, 2019; González de Molina & Toledo, 2014; Haberl *et al.*, 2019). According to Gerber & 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 particular resource use. Yet the originality of the approach lies in having a robust theoretical basis as a consequence of a sophisticated combination of concepts belonging to complex systems science (Giampietro, 2019b; Giampietro *et al.*, 2012, 2013, 2014; Giampietro & Renner, 2020; Renner, Louie, *et al.*, 2020) which can deal with the epistemological challenges associated with the consideration of different aspects relevant for the discussion over sustainability. This biophysically grounded framework is open to pluralities of values and concerns, a feature that makes the methodology capable of handling incommensurability issues1, identified as relevant in sustainability science research agendas (Weitz *et al.*, 2018).

Over the more than 20 years since its introduction, MuSIASEM accounting has been used for different integrated assessments. Moreover, various improvements have crystallized into a more sophisticated version2. Indeed, MuSIASEM has advanced in handling quantitatively multiple dimensions (energy, water, food, raw materials, emissions, waste, human activity, land use, power capacity) and multiple levels (process, sub-sector, sector, average society) across scales (per hour, per year, per m2). Epistemological tools such as the end-use matrix and the environmental pressure matrix have been refined, taking trade effects into consideration. Additionally, ontological issues have also gained in depth. We firmly believe that all these advances require an effort of discussion and synthesis with reference, also, to the most recent publications using the methodology.

In a nutshell, the aim of the paper is threefold: (i) to rediscuss and update the relevance of the theoretical foundations of MuSIASEM; (ii) to provide a synthetic overview of the analytical tools available in the methodology to assess different aspects of the current sustainability crisis; and (iii) to clarify the not always well-understood peculiarities, potentialities and limitations of the analytical framework. This should lead to an informed application of MuSIASEM and a greater understanding of complementarities with other methodologies. In this way, MuSIASEM could bridge and complement analysis focused on processes

[1] Incommensurability means that there is no common standard of evaluation for certain values belonging to different dimensions (Martinez-Alier et al., 1998).
[2] So-called MuSIASEM 2.0 was developed within the Horizon 2020 project MAGIC (short for Moving Towards Adaptive Governance in Complexity — https://magic-nexus.eu/).

and objects such as Life Cycle Analysis (European Union Joint Research Center, 2010) with a systemic perspective and analysis focused on flows such as MEFA (Fischer-Kowalski & Haberl, 2007) with the key entanglement with fund elements3.

The paper is organized as follows: section two presents the basic ideas behind MuSIASEM as regards the characterization of social-economic systems, 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 closes with some limitations and concluding remarks.

MUSIASEM: REVISITING AND UPDATING ITS HETERODOX RATIONALE

Building on Spash (2015), a vision seems to be required before we can proceed. From this understanding, empirical reflection can follow. Therefore, the bases of MuSIASEM as regards its understanding of social-economic systems, the economic process and sustainability are synthesized.

How does MuSIASEM view social-economic systems?

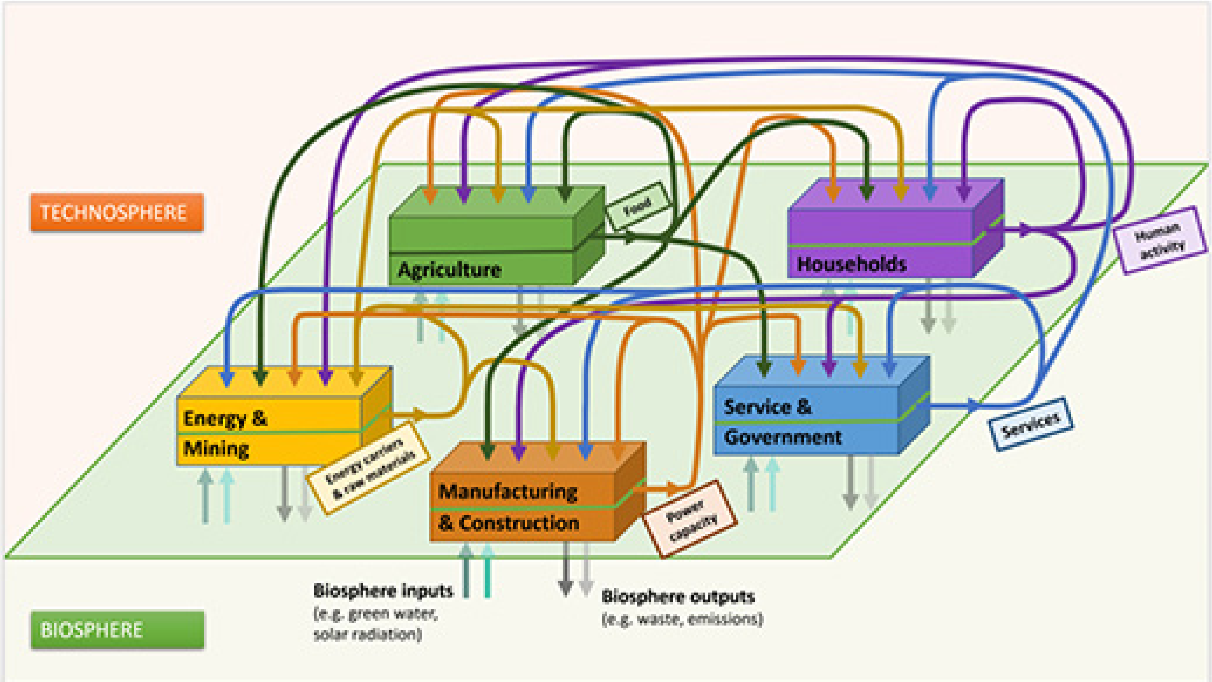
From the MuSIASEM perspective, social and natural systems are complex adaptive systems (Gell-Mann, 1994; Holland, 1995, 2006) and should be studied considering them as entangled (Giampietro, 2019a). Treating a system as complex presents several epistemological challenges (Ahl & Allen, 1996). Mainly, the behaviour of the whole is not evident from the study of its parts (Cilliers, 1998). Patterns 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 (Giampietro *et al.*, 2006) where social-economic systems are considered integrated wholes whose properties are determined by the dynamic connections among functional and structural elements (e.g. transport function could be performed by different structural elements such as a bike or a scooter; a bike could perform different functions of transport or recreation). The methodology 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. These constituent components express different functions, associated with a wide variety of useful outputs or end uses (i.e. what is required by society). In turn, they are constrained by biophysical limits such as resource availability or performance capacity, associated with the characteristics of the structural elements shaping them (i.e. what is admissible in biophysical terms). For example, the agriculture sector generates several useful outputs such as biomass input to the energy sector or food inputs to the household sector. The supply of all these inputs is constrained by the amount and characteristics of the structural elements that make up the agriculture sector, i.e. the productive capacity of different types of farms determined by technical viability (e.g. labour and capital), and also by the availability of ecological services, i.e. the availability of production factors such as soil, solar radiation or biodiversity, made available by natural processes. At the same time, production processes in the agricultural sector require inputs from the other compartments of society. That is, the other compartments of society must be willing and capable of providing the required secondary inputs needed by the agricultural sector to operate (e.g. labour, technology, energy carriers) in exchange for the products of this sector.

MuSIASEM links the perception and representation of an economic system with concepts such as interdependence and complementarity. In this framework, a social-economic system is considered as a relational metabolic network in which constituent components stabilize each other in an impredicative set

[3] Drawing on Georgescu-Roegen (1971), fund elements maintain their identity over the course of time of analytical representation. Examples of fund elements include human activity, land, and sustainably managed aquifers. On the other hand, flow elements change their identity during the analytical representation. Examples of typical flow elements include energy, food and waste.

of relations (Renner, Louie, *et al.*, 2020). In other words, we should expect that 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 with the others to sustain and reproduce the whole network. Thus, the constituent components of an archetypical modern social-economic system depend on each other in terms of essential inputs (see Figure 1): (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 (labour and consumption) to the rest of the constituent components; (ii) primary sectors (agriculture, energy and mining) use human activity that comes from the household, primary inputs from the environment (i.e. biosphere inputs), and secondary inputs 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 (i.e. power capacity) 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 the people that ask for services (Velasco-Fernández, Dunlop, *et al.*, 2020). Moreover, this set of relations between constituent components (in the technosphere) requires, in turn, constant interaction with the environment, dumping waste and emissions (biosphere outputs) and obtaining goods and services (biosphere inputs). The consideration of this necessary relationship implies modifying our level of observation. What we see 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.

FIGURE 1. SOCIETAL CONSTITUENT COMPONENTS´ ENTANGLEMENTS IN THE TECHNOSPHERE AND BIOSPHERE



Source: Adapted from Renner, Louie *et al.* (2020)

How does MuSIASEM view 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 psychic structure of the society (Luhmann, 1995) associated with the affective interactions experienced during the production and consumption of goods and services. Following the same line of reasoning, the ultimate goal of the economic process in MuSIASEM is not that of producing as many goods and services as possible (ecosystems and households also produce goods and services), but to ensure the maintenance, reproduction and adaptability of their constituent components. Indeed, the production and consumption of goods and services is only relevant if this process is capable of expressing the emergent property typical of complex adaptive systems, i.e. reproducing themselves while learning how to adapt to the changing conditions of their contexts (Giampietro & Mayumi, 2018). This change in perspective moves attention from productivism to a different set of essential factors defining the economic process. This shift is in line with a vision of economics as a science of social provisioning which seeks to understand how societies organize the flow of goods and services necessary to maintain and reproduce themselves in the context of historically specific systems and structures (Pirgmaier & Steinberger, 2019; Spash, 2020).

With the above in mind, we can conclude that the metabolism of a social-economic system is not an analogy of the biological notion of metabolism for understanding human-nature interactions (Fischer-Kowalski, 1998; Infante Amate *et al.*, 2017), but a fact (Giampietro *et al.*, 2020). Human systems are maintained and renewed through their continuous interactions with the environment. They are integrated wholes inseparably linked to metabolic and dynamic processes of change. Therefore, social-economic systems are metabolic-repair systems of the type explored in relational biology (Renner, Louie, *et al.*, 2020). 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 of a process of replication, metabolism and repair.

How does MuSIASEM consider the sustainability of social-economic systems?

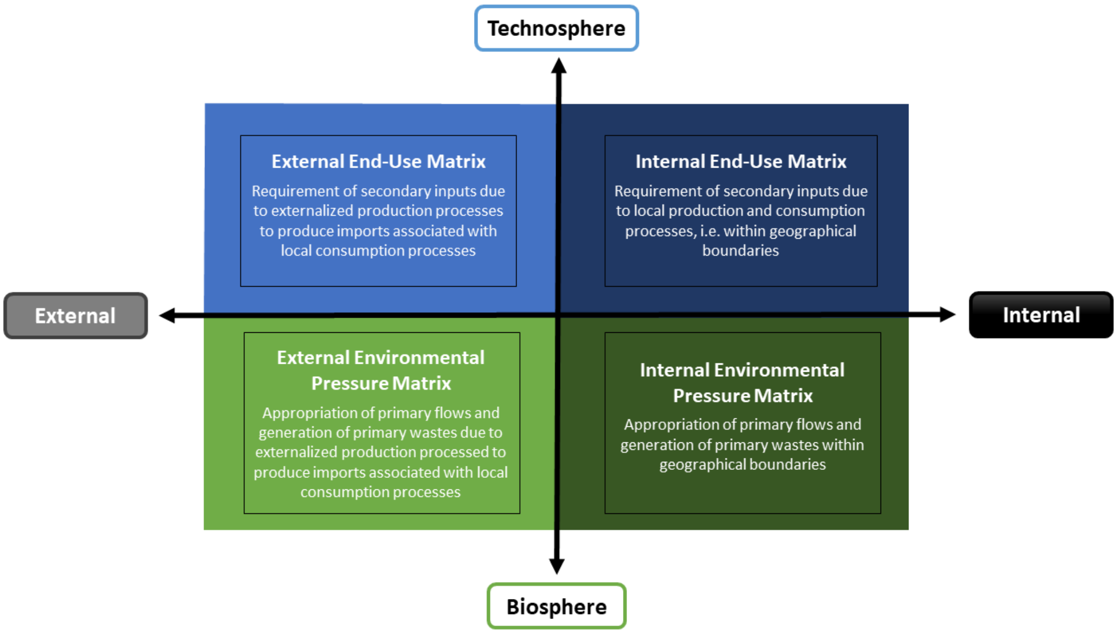
MuSIASEM opens the way for a quantitative and qualitative contextualization of the sustainability of social-economic systems based on the study of their metabolic pattern. The metabolic pattern refers to the interdependent processes of conversion of energy and materials inputs in a given society, used to reproduce itself. This analytical concept makes it possible to study the entanglement of different types of metabolic flows and funds across levels and scales of analysis. If sustainability is understood as the commitment of human societies to preserve the essential elements of their identities in line with environmental constraints (i.e. respecting the biophysical processes and thresholds of the planet and local ecosystems), analysis of the metabolic pattern generates different indicators referring to different levels of observation capable of addressing different sustainability concerns. In this way, it becomes possible to integrate:

1. An external view related to the concept of feasibility and associated with processes outside human control. Feasibility checks the compatibility of the *environmental pressures* associated with the metabolic pattern of any society (see section 3.1), with the existence and severity of external biophysical constraints. This involves constraints that result from the interaction of social-economic systems with ecological systems, both on the supply side (e.g. appropriation of primary flows —they cannot be produced by human technology, first principle of thermodynamics— such as oil, water or minerals, which need primary supply provided by nature) and the sink side (e.g. primary wastes and emissions such as greenhouse gases and plastic waste). This view is translated into a quantitative assessment associated with the *environmental pressure matrix*. Feasibility is related to the natural constraints limiting production and consumption, and raises questions such as: how much land and water are required for producing domestic food consumption? Or, are there sufficient lithium reserves to replace the entire fleet of combustion vehicles with electric ones? This analysis could be associated with planetary boundaries (Rockström *et al.*, 2009).

2. An internal view related to the concept of viability and associated with processes under human control. Viability checks the severity of internal biophysical and economic constraints operating inside the social-economic system. These constraints include technological capability, economic viability and labour supply/shortage. The requirements of these elements are also associated with socio-demographic variables (Velasco-Fernández, Pérez-Sánchez, *et al.*, 2020) and the terms of trade (Pérez-Sánchez *et al.*, 2021). In fact, one of the key elements of the methodology is the analysis of the profile of time use as an emergent property of the societal organization and as a relevant internal constraint in case of a shortage of human time in one or more critical functions in society (Manfroni, Velasco-Fernández, *et al.*, 2021). Viability requires characterizing the *state*, i.e. looking inside the black box for the internal metabolic characteristics of the structural and functional compartments of the social-economic system. This view is translated into a quantitative assessment associated with the *end-use matrix*, based on analysis of the use of secondary inputs —produced by human exploitation of primary flows and compatible with the different typologies of power capacity that use them to generate end uses— i.e. energy carriers (e.g. electricity, fuels), distributed water for different societal uses, and processed materials. Viability is related to the technical and economic constraints affecting production and consumption and raises questions such as: how are the secondary inputs used in different societal compartments to reproduce and adapt? What percentage of human activity is allocated to the primary sector? Or, what is the welfare level (measured as the percentage of human activity allocated to the service sector) of the society?
3. A normative view related to the concept of desirability. Desirability refers to the perceived acceptability of the living conditions and moral responsibility associated with the expression of the metabolic pattern. This expression makes it possible to produce a set of social practices (Shove *et al.*, 2012) where affective and technical relations are entangled in either sustainable or unsustainable ways. This implies that to assess desirability it is necessary to extend the analysis beyond biophysical variables by considering also matters of values, desires and beliefs, as well as cultural, social and political arrangements. Addressing the desirability of the metabolic pattern of a social-economic system requires a reflection that calls for a post-normal science rationale (Funtowicz & Ravetz, 1993), i.e. forms of knowledge based on participatory and deliberative processes, and raises questions such as: assuming that a transition to 100% renewable energy is feasible (i.e. possible materially, finding enough minerals and land to build the energy infrastructure) and viable (i.e. possible socioeconomically), will the readjustment in everyday practices because of this transition find social acceptance?

MuSIASEM establishes a framework of analysis capable of establishing a set of expected relations concerning these different aspects of sustainability (feasibility, viability and desirability). An integrated analysis of these different aspects requires the simultaneous use of non-equivalent and non-reducible definitions of constraints or limits of a different nature (external limits associated with feasibility and internal limits associated with viability and desirability). To this end, MuSIASEM uses a toolkit comprising an interrelated set of matrices that supplies an integrated, multi-scale, quantitative representation of the functioning of the metabolic pattern. It explicitly considers, also, the degree of openness of the social-economic system determined by trade, i.e. accounting not only for the biophysical processes taking place within each system's geographical boundary (e.g. fuels refined in Spain) but also for those supporting each system's metabolic pattern, taking place elsewhere (e.g. oil extracted elsewhere to produce the fuels refined in Spain). This tool-kit can be used: (i) in diagnostic mode to obtain an in-depth understanding of the biophysical foundations of the system under analysis, identifying critical aspects in the form of indicators that can be tailored to relevant sustainability concerns; and (ii) in anticipatory mode, exploring scenarios based on the adoption of benchmarks, raising "what if" questions concerning possible reactions to changes introduced (policies and innovations). Because of the consideration of the effects of externalization (the degree of openness), the toolkit characterizing the factors determining the state and the pressures is organized into four matrices (Figure 2). Two different types of matrices are used to characterize the factors of viability, observed inside the border —the internal end-use matrix— and outside the border —the external end-use matrix. And two matrices are used to characterize the factors of feasibility, observed inside the border —the internal environmental pressure matrix— and outside the border —the external environmental pressure matrix.

FIGURE 2. MUSIASEM TOOLKIT COMPRISING AN INTERRELATED SET OF MATRICES



Source: Own elaboration

Practical examples in which this analytical toolkit is used in diagnostic mode can be found, among others, in the characterization of the uses of different forms of energy carriers (electricity, heat, fuels) for the various tasks performed in the city of Barcelona, showing how commuters and tourists affect energy consumption per capita targets (Pérez-Sánchez *et al.*, 2019); the analysis of the environmental and economic performance of different economic activities in the Mediterranean island of Menorca, exposing the tensions between economic productivity and environmental pressures (Marcos-Valls *et al.*, 2020); or, pointing out the impossibility for the EU of re-internalizing the production of its massive feed imports (Cadillo-Benalcazar, Renner *et al.*, 2020). On the other hand, a practical example of using this analytical toolkit in anticipation mode can be found in Renner, Cadillo-Benalcazar *et al.* (2020), which uncovers blue water and land requirements breaching environmental limits if a dramatic re-internalization of agricultural production takes place in the EU.

MUSIASEM KEY THEORETICAL CONCEPTS.

This section discusses and updates key theoretical concepts in the literature on MuSIASEM, which are not always well explained and understood. Each concept springs from different roots within the tree of complexity science and touches on key aspects to consider. Table 1 summarizes their main characteristics.

TABLE 1. COMMON THEORETICAL CONCEPTS IN THE LITERATURE ON MUSIASEM

Theoretical concept	Field	Level of observation	Main characteristic
State-pressure relations	Non-equilibrium Thermodynamics (Nicolis & Prigogine, 1977; Prigogine & Glansdorff, 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.
Holon and holarchies	Hierarchy Theory (Ahl & Allen, 1996; Allen & 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 intangible (notional) when perceiving and representing a complex system.
Relational Analysis	Relational Biology (Louie, 2017; Rashevsky, 1935; Rosen, 2000, 2005)	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: (i) in relation to the interaction with other parts inside the technosphere (secondary inputs and outputs); and (ii) in relation to the interaction with the biosphere (primary flows on the supply and sink side).
Semiotic process	Biosemiotics (Barbieri, 2019; Emmeche & Kull, 2011; Kull *et al.*, 2019; Pattee, 1995)	Human societies not only exchange materials and energy with the environment but also information	Existence of entities which organize our experience, even though they are not tangible (emotions, fears, beliefs, political processes). These answer questions such as "who are we as a society? Or, "what are our goals?" determining the metabolic relation with nature, i.e. 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 and other material inputs (in the hypercyclic part) —catabolism; and (ii) expressing other required behaviours (in the dissipative part) such as maintaining and updating social institutions —anabolism.

Source: Own elaboration

State-Pressure relations

◇ Main idea

The major problem human societies face is sustaining themselves. Social sustainability, i.e. maintaining a certain state in the technosphere (associated to positive or valued parts of the current way of life), is irremediably linked to environmental pressures and impacts on the biosphere.

◇ Theoretical background

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 & Renner, 2020; Odum, 1971; Simon, 1962). Both classes are composed of open systems which require the existence of favourable 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 be explained under a perspective of non-equilibrium thermodynamics, using the concept of dissipative structure (Nicolis & Prigogine, 1977; Prigogine & Glansdorff, 1971). Social-economic systems are dissipative in the sense that they have 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 (they can literally die). In consequence, these systems must be capable of monitoring and reacting to changes in their surroundings to remain capable of using flows of negative entropy.

In this regard, Schrödinger (1967) proposed the term "negentropy" as the reciprocal of entropy. Living systems are able to reduce their internal entropy (or increase their negentropy or internal order) at the expense of the free energy taken from the environment and returned to it in a degraded form. In particular, the flows of negative entropy available in the environment (favourable boundary conditions associated with needed primary resources, e.g. fertile soil) are used to sustain a process of exergy degradation, i.e. a process of conversion of secondary inputs (e.g. food) into useful work carried out under expected and controlled conditions. That is, the environmental pressures sustained by the environment —(-dSe) using the iconic representation proposed by Prigogine (1961)— compensates for the positive entropy generation rates (+dSi) associated with the maintenance of the state of the complex internal organization.

◇ Why is the state-pressure concept important in MuSIASEM?

MuSIASEM uses Georgescu-Roegen's flow-fund model, his most highly-developed analytical contribution after the 1970s (Couix, 2018), under a framework of non-equilibrium thermodynamics to improve the accounting for state-pressure relations. Funds are the underpinning components of SES, belonging either to the biosphere (e.g. soils, aquifers) or the technosphere (e.g. human activity, power capacity). Flows may be natural resources (e.g. primary flows such as crude oil or solar energy) or transformed resources (e.g. secondary inputs) such as blue water[4] or energy carriers, and include also wastes, i.e. unwanted by-products such as CO_2 emissions. The distinction between funds and flows is essential to define a metabolic system and characterize its metabolic pattern, both: (i) in quantitative terms (the size of the flows and the funds); and (ii) in qualitative terms, when considering flow/fund ratios and fund allocation patterns (Velasco-Fernández, Pérez-Sánchez, *et al.*, 2020). By looking at the size of fund elements and their metabolic rate (flow rate per unit of fund) in the technosphere compared to the size of ecological funds and their metabolic rate in the embedding environment, we can study the

[4] The definition of blue water includes the fraction of water found in lakes, rivers and reservoirs and that usually needs to be distributed. On the other hand, green water is defined as the water contained in the soil that can be used only by plants for evapotranspiration and that can be neither distributed nor treated before use (Giampietro et al., 2014).

factors determining a given state-pressure relation. This coupling of the size of the fund elements of the society with the size of funds elements of the ecosystems helps to identify unsustainable use of biophysical resources. Finally, this concept facilitates a clear definition of sustainability: a system is sustainable if its reproduction maintains the integrity of fund elements both in the technosphere and in the biosphere.

In practical terms, the operationalisation of the state-pressure through the flow-fund model implies that flows are always analysed in relation to funds, never isolated or with other flows. This accounting does not focus only on quantifying flows but connects funds (the agents and transformers of processes) and flows (the elements that are utilised and dissipated). For examples, see Giampietro & Bukkens (2022), where the irrelevance of energy efficiency indicators obtained by calculating flow/flow ratios for sustainability analysis (e.g. carbon intensity or energy intensity indicators) is discussed. Also, Velasco-Fernández, Pérez-Sánchez *et al.* (2020), where a multi-scale flow-fund characterisation is used to show the state-pressure evolution of China due to its modernisation considering human activity as a fund element and energy throughput and value-added as flow elements.

Holon and holarchies

◇ Main idea

The pre-analytical definition of "what is observed and how" is essential in determining a quantitative output. The concept of holon points to the elusive nature of complex systems and the impossibility of them having a unique characterization.

◇ Theoretical background

The term "holon" was proposed by Arthur Koestler (1967) to address the epistemological predicament consisting in the fact that some entities are in many senses wholes but cannot be understood without recognition of the 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 & Allen, 1996; Allen & Giampietro, 2014; Allen & Starr, 1982; Giampietro, 1994) further elaborated on 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 & Mayumi, 2018). Depending on the scale adopted, "an element" can be considered a structural whole —e.g. a human being made up of organs (the local-scale view)— or a functional part of a higher hierarchical level —e.g. a human being part of a household (the large-scale view). The large-scale view defines a relevant functional type associated with the ability to express an expected behaviour defined in relation to the context, i.e. the rest of the network the element belongs to. The local-scale, for cons, defines a pertinent structural type, i.e. the organized structure required to perform the specified function. 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 *et al.*, 2006). A functional type can map onto different structural types and a structural type can have different functions. Besides, both structural and functional types are notional entities that cannot express agency. Agency can only be realized by an instance of these types, a specific tangible realization of the combination of the two types. In this sense, when representing elements of complex systems, we think of 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) that coincide only in part with the definition of the types.

◇ Why is the concept of holon important in MuSIASEM?

The concept of holon allows an understanding of social-economic systems as holarchies, metabolic networks embedding structure and function. As a result, the transformative services of system components (the transformation of input flows into output flows) can be analysed according to different logics: the input profiles of a series of functional elements and those related to a set of structural elements. The quantitative assessments concerning the two logics do not necessarily map onto each other. The assessment of the metabolic characteristics of the functional elements —the notional representation of, for instance, "cereal production"— is different from that of the structural elements —the technical representation of different production processes (e.g. a wheat production system, a rice production system or a corn production system)— all mapping onto the same function, "cereal production" at a higher level. This entails that, depending on the pre-analytical choice of the analysis, i.e. the definition of the structural elements making up the functional component, different quantitative results can be generated to characterize the metabolic characteristics (i.e. inputs and outputs) of a given task. For example, "cereal production" can be defined by using different combinations of production processes (wheat, rice, corn) with different percentages in the mix.

To deal with this issue MuSIASEM adopts two complementary views when analysing metabolic requirements (Giampietro *et al.*, 2014):

. A top-down view —generating information about functional elements (a notional representation): this logic uses large-scale assessment based on aggregate statistical data to obtain the value of the total amount of inputs used by a given function in the system (e.g. consumption of electricity in the residential sector or consumption of fuels in the transport sector for mobility).

. A bottom-up view —generating information based on technical characteristics of structural elements: this logic uses local-scale assessments based on direct measurement of coefficients (when dealing with instances of structural elements —e.g. a particular nuclear power plant) or values derived from benchmarks (when dealing with structural types —e.g. a hypothetical nuclear power plant) to characterize local operations of technical elements, i.e. a given technology expressing a biophysical set of transformations (e.g. specific energy requirements for different houses —single or multi-family houses— or for different devices used for mobility in the transport sector —cars, motorcycles and trucks).

In short, considering systems as holarchies implies the need to analyse them from different hierarchical levels and understand their elements as holons. In turn, the use of two complementary perspectives to define the elements that make up metabolic systems ensures the great robustness of the analysis allowing a double check on the coherence of data referring to different observations. Finally, the difficulty in having a substantive one-to-one mapping between the accounting of the characteristics of structural and functional elements and/or between the characteristics of types vs instances suggests prudence concerning any quantitative results. For a practical example of the elusive nature of complex systems and the different types of uncertainty that may arise when describing a societal energy system, see Di Felice *et al.* (2019).

Relational analysis

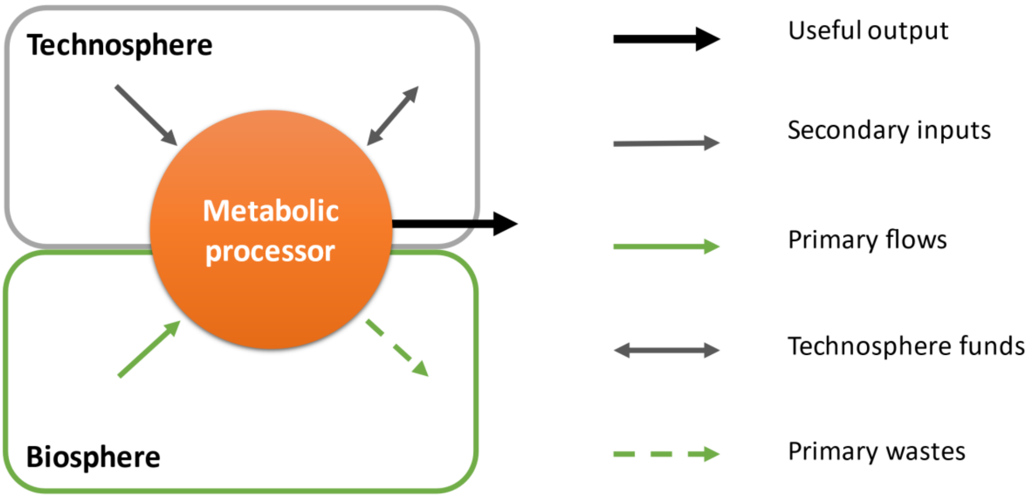
◇ Main idea

The concept of metabolic processor represents a solution to deal with the epistemological predicament of describing holons, i.e. describing the characteristics of both structural and functional elements.

◇ Theoretical background

The term "relational analysis" is based on the term "relational biology" (Louie, 2017; Rashevsky, 1935; Rosen, 2000, 2005) 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, whether a functional compartment or a structural element, is an open system in itself that expresses an expected pattern of "behaviour" in terms of consumption of inputs (coming either from the technosphere or the biosphere) and the expression of a useful function, i.e. the supply of the output. A relational analysis based on the concept of metabolic processors is used to describe the characteristics of the structural and functional elements of SES. More specifically, a metabolic processor conveys five sets of inputs/outputs (see Figure 3): (i) secondary inputs from the technosphere (e.g. electricity, fuels, food); (ii) required funds under human control from the technosphere (e.g. hour of human labour, hectares of land use, rate of power capacity); (iii) internal outputs, i.e. useful flows or funds generated by metabolic elements and used by other elements in the technosphere (e.g. the production of food in the agricultural sector or the performance of care activities in the household sector); (iv) primary flows extracted from the biosphere (e.g. green water, water removed from aquifers, coal); and (v) primary wastes discharged into the biosphere (e.g. pollutants, nitrogen from fertilizers, GHG emissions).

FIGURE 3. THE METABOLIC PROCESSOR



Source: Adapted from Di Felice *et al.* (2019)

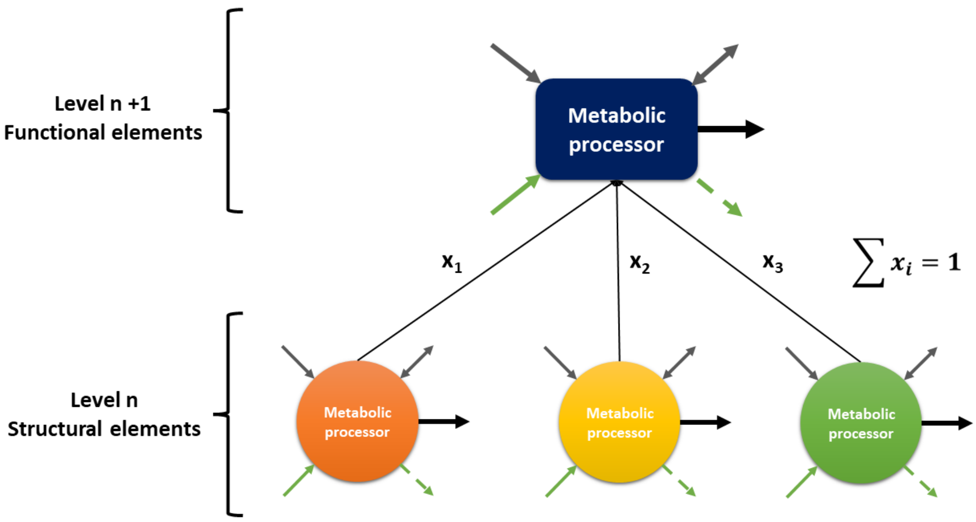
◇ Why is relational analysis important in MuSIASEM?

Relational analysis enables operationalising a holistic and complex perspective of sustainability issues. This vision is crucial due to several wicked problems (Rittel & Webber, 1973), chicken-egg relations (Giampietro & Mayumi, 2018) and complex scaling effects (Cabello *et al.*, 2019) taking place in SES that are overlooked by reductionist perspectives and silo governance (Scott & Gong, 2021). In this sense, MuSIASEM is capable of capturing in a non-deterministic manner: (i) how the different parts of a system are related, e.g. the production of peak electricity in the energy sector allows the maintenance of a set of social practices in the household sector; (ii) how parts of the system change, e.g. technological innovation of a particular industry; (iii) how the size of the constituent components change, e.g. the relative size of the manufacturing and construction sector in relation to the whole SES; and (iv) how these changes co-evolve by affecting other parts generating systemic change, e.g. the Jevons paradox (Giampietro & Mayumi, 2008). Considering these different types of relations is crucial to understand why MuSIASEM analysis is so conservative in developing projections over the evolution of SES, building exploratory scenarios rather than predictive ones.

When implementing relational analysis, different nodes of a metabolic network, i.e. the different holons of a SES, can be represented by a set of expected relations over metabolic processors[5]. The input/output flows tied to a metabolic processor are expressed at the level of individual structural elements, but can also be assessed in notional terms at the level of functional elements by associating specific combinations of structural elements (at a given level) to the identity of functional elements (defined at the level above, see Figure 4). For instance, we can aggregate the various different processes used in the production of biodiesel (the different crop production processes associated to the operation of organized structures, i.e. the different typologies of biofuel production plants) to obtain the functional element "biodiesel production". Moreover, we can also see the relative contribution of each functional node to the whole (e.g. biodiesel production in relation to the energy system). The aggregate sets of inputs and outputs can then be used to generate matrices (the end-use matrix and the environmental pressure matrix made up of fund and flow elements), characterising the overall SES. However, in this way, we just get socio-environmental pressures for discussing feasibility and viability aspects. Except for flows directly mapping into global ecosystems as greenhouse gas emissions, the analysis of potential environmental impacts requires focusing on the individual structural elements (i.e. local production processes affecting ecological funds).

Different applications have been developed using the concept of processor to analyse some critical sustainability issues, such as the socio-environmental impacts of the qualitative change of available oil reserves (Manfroni, Bukkens, *et al.*, 2021; Parra *et al.*, 2020); the implication of changing an export-oriented energy policy to one that prioritizes local consumption (González-López & Giampietro, 2018); or the potential problems with large-scale use of alternative feeds in salmon aquaculture (Cadillo-Benalcazar, Giampietro, *et al.*, 2020).

FIGURE 4. AGGREGATION OF STRUCTURAL ELEMENTS IN A HIGHER-LEVEL FUNCTIONAL ELEMENT



Source: Adapted from Giampietro *et al.* (2020)

[5] It is worth mentioning that two databases of structural processors have been generated (Cadillo-Benalcazar & Renner, 2020; Di Felice, 2020) to conduct assessments of the performance of the food and energy sectors.

The semiotic process

◇ Main idea

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.

◇ Theoretical background

Whereas simple physical systems may be well understood as simply behaving in a thermodynamic fashion, we cannot understand ecological or social systems without invoking meaning and significance (Barbieri, 2019; Emmeche & Kull, 2011; Giampietro *et al.*, 2006; Giampietro & 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 (syntactics) used 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 the knowledge is validated. If not, new explanatory models must be generated until "semantic closure" is obtained (Pattee, 1995), i.e. when all the steps between semantics, syntactics and pragmatics are coherent in relation to the purpose of the final party responsible for evaluating the process.

In the case of human societies, achieving semantic closure is an intricate and conflictive process, especially in sustainability issues where different agents, using non-equivalent criteria, have contrasting goals, perceptions and representations of what should be considered relevant. In this sense, the existence of a political process defining the identity (i.e. what we must sustain) and determining the priorities over the problems to be solved by society as a whole, is a special component of the semiotic process of human societies (Giampietro, 2019b). The semiotic process reveals the fact that value systems are an essential part of human activity. Different value systems co-exist and they are never equally influential within society. Due to the existence of power asymmetry in the political process it is important to avoid the hegemony of partial and particular perspectives and agendas in the political process in relation to the problems to be solved. A definition of concerns to be addressed that is 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 that omits important aspects to be considered for adaptation and sustainability. That is, predominance of old perspectives due to elites remaining in power can lead to a lack of accountability (are they still useful?) and transparency (are they still justified?), hindering the process of adaptation in the holarchy according to new situations (is more growth desirable?). This is especially relevant in the current circumstances because of the supremacy of OE narratives in the decision-making process.

◇ Why is biosemiotics important in MuSIASEM?

Biosemiotics is relevant for MuSIASEM because it allows us to navigate among the epistemological troubles when representing SES across scales and dimensions: a good or bad explanation depends on the problems faced, which makes that models and explanations are not right or wrong, but practical or useless. In this sense, the semiotic process has profound implications when using MuSIASEM. Humans represent only a shared perception of reality, not the actual reality in their scientific analysis (Giampietro, 2003). When providing scientific evidence to guide policy, we have to take into account the implications of the pre-analytical choice of a given perspective. That is, any observer's point of view must be integrated into a larger knowledge process. The selection of models, data and monitoring that result into an agreement about the existence of "facts", used to guide specific actions, are the result of the original choice of a given narrative that is relevant for addressing particular concerns. 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 and historical process. Consequently, any discussion over sustainability entails a political or ideological dimension that must be explicitly acknowledged and addressed in the pre-analytical phase. Consideration of different observers uncovering the existence of incommensurability of values (Munda, 2008), especially when modellers are part of the system, and a semiotic process which is not external to power relations, turns MuSIASEM into a post-positivist approach that recognizes pluralities of values and concerns[6].

Some papers illustrating with practical examples the relevance of the semiotic process when handling sustainability issues can be found when discussing: the ethical, conflictive and relevant attributes associated with the process of milk production for different stakeholders (Giampietro & Bukkens, 2015); the political and epistemological implications of the representations of the resource nexus (Giampietro, 2018); or the different pre-analytical visions concerning the circular bioeconomy with different implications for sustainable growth (Giampietro, 2019a).

Dynamic Energy Budget

◇ Main idea

A social-economic system has to invest energy to obtain energy but at the same time also has to invest energy in expressing other purposes such as maintaining and updating social institutions.

◇ Theoretical background

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 such as Lotka (1922), Zipf (1941) and White (1943) developed this idea from different fields. The concept of the dynamic energy budget for the study of social-economic systems is based on previous works in the field of system ecology. Analysing ecosystem structures, Ulanowicz (1986) found that the network of matter and energy flows conforming an ecosystem can be divided into 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 purely 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 favourable gradients found in nature); and (ii) the anabolic part (the one expressing the activity of reproduction and control).

According to this conceptual distinction, the various functional compartments of a social-economic system can be divided between: dissipative sectors, i.e. sectors involved intensively in the metabolism of biophysical flows and the 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 than they use for their own metabolism (e.g. the 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 differentiation of activities that society can afford in the dissipative part (Giampietro *et al.*, 2012). That is, there must be a balance between the energy and materials required to express the various societal functions (in all the constituent components of the society) and the supplied flow generated only by the hypercycle part. This implies a forced relation or

[6] In practice, this means that the extent and grain of the observed system —macroscope, mesoscope and microscope in the jargon— as well as the observable attributes —the variables— must be selected according to the observer's concerns.

dynamic equilibrium in the impredicative relations between what is achieved (a supplied flow of energy and materials generated by the hypercyclic compartments) and what is expected (a material standard of living determined by the aspirations of people living in society). Or in other words, external limits (associated with the concept of feasibility, i.e., environmental sources availability and sink carrying capacity) and internal limits (associated with the concept of viability, i.e., the human, technological and institutional capacities) determine what is possible to happen, delimiting the realm of the political dispute (associated with the concept of desirability, i.e., hegemonic values and political contingencies). Consideration of fund and flow variables when characterizing the metabolic identity of human societies implies that both variables act as constraints in the viability of this dynamic equilibrium. Both natural resources from the biosphere and human time and human-created goods from the technosphere are necessary to produce and consume goods and services, supporting an idea of "strong sustainability" (Couix, 2019).

◇ Why is the dynamic energy budget important in MuSIASEM?

The dynamic energy budget points out the way in which societies depend on the quality of energy sources. However, post-industrial societies present a high specialization in the service sector, with a percentage of around 70% of the total paid work hours in that sector (Velasco-Fernández, Pérez-Sánchez, *et al.*, 2020). These societies rely on imports to compensate for their relatively low production in their hypercycle sectors in relation to their domestic consumption (Manfroni, Velasco-Fernández, *et al.*, 2021). Therefore, externalization must be considered and not only for energy issues to understand the factors allowing the expression of a given metabolic pattern. For instance, accounting for the externalized carbon emissions of the energy sector raises total GHG emissions of the sector by 60% on EU average (Ripa *et al.*, 2021), or the overall goods and services consumed in the EU involve the work of more than 130 million extra virtual workers (Pérez-Sánchez *et al.*, 2021). In this sense, MuSIASEM enables consideration of the burdening shift that favourable terms of trade impose on other SES by providing a notional definition of a given set of production processes associated with a given quantity of imported commodities in relation to food and energy. These representations quantify both end uses (secondary inputs and fund elements) and environmental pressures (primary flows and wastes) embodied in imports. Thus, for example, it would be possible to characterize domestic cereal production (from observed domestic supply systems) and imported cereal production (from virtual supply systems assessed with notional metabolic processors based on expected values from theoretical technical coefficients) to obtain a holistic view of biophysical requirements in the food sector. For examples of quantitative analysis taking into account externalization see Renner, Cadillo-Benalcazar *et al.* (2020), Pérez-Sánchez *et al.* (2021) and Ripa *et al.* (2021).

FINAL CONSIDERATIONS

The most complex challenges facing humanity in the 21st century, including climate change, biodiversity loss, peak oil and others (Heinberg, 2007), have to do with the existence of biophysical limits that seem to be incompatible with the aspirations of a growing population seeking better standards of living both in developed and developing countries. These limits (together with remaining poverty and inequality) affect the stability of the economic process or, in other words, the feasibility, viability and desirability of the different types of metabolic pattern expressed by different instances 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. However, in spite of the urgency of this need, most institutions and social actors remain in denial. The dominant reliance on OE narratives filters out this uncomfortable knowledge. As a result, the current unsustainability of the existing pattern of economic development is a subject carefully avoided 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 new perceptions and narratives are necessary in order for us to be able to envision other societal configurations. We need new epistemic tools capable of: (i) informing this deliberative process by checking the quality of different narratives on sustainable social practices; and (ii) flagging the implausibility of many delusional technoscientific imaginaries.

The MuSIASEM methodology in its more mature version provides an accounting scheme to carry out a coherent analysis of the biophysical factors determining the sustainability of social-economic systems. Moreover, its main features —e.g. exploring the relations between environmental, social and economic systems, acknowledging incommensurable values, highlighting a strict focus on strong sustainability, including intangible elements (values, desires, narratives) when tackling sustainability crisis or stressing a biophysical reality with its laws and conditions— are faithful to key aspects of ecological economics, especially to positions incompatible with OE (Melgar-Melgar & Hall, 2020).

Possible weaknesses in the methodology are basically associated with its performance. First, the integration of different dimensions over different levels of analysis requires a significant amount of data. This information is not always readily available for all years and when available is not always produced with the same system categorization. This entails extra work to re-arrange data that are in general available only indirectly. Transdisciplinary analysis requires disaggregated data that should be made publicly available. Second, the information space generated by MuSIASEM is extremely dense. This entails the need to adopt software to be used for developing decision support tools in order to be able to involve non-experts in the discussion. In relation to this point, the clear transparency of the set of relations in the accounting should make this work of visualization easy. Last, but certainly not least, MuSIASEM can be used to check the plausibility of policies and the robustness of the scientific evidence characterizing the expected future by identifying the metabolic characteristics of the holarchies, the strength of the hypercycles and the level of openness of the metabolic pattern. In the existing situation, this check has very rarely generated pleasing results for the environment flagging the existence of "uncomfortable knowledge" in existing sustainability discussion. That is, sustainability analyses based on MuSIASEM show the implausibility of proposed policies or sociotechnical imaginaries. For this reason, so far, applications of MuSIASEM have not been welcomed by either governments or private companies. The legitimacy of the establishment is based on claims that political choices are based on "scientific evidence", even though, very often, what is used in actual decision-making processes is "policy based evidence" (Marmot, 2004; Strassheim & Kettunen, 2014), i.e. model representations narrowly built to validate pre-defined targets.

Despite the aforementioned potentialities and criticalities of MuSIASEM, its unconventional and transdisciplinary theoretical foundations represent a difficult challenge to most people approaching the methodology for the first time. Consequently, the lecture on specific case studies is highly recommended (see reference section). However, a synthetic and updated discussion of the most relevant and recent theoretical foundations is lacking and for this reason, the authors felt that was necessary to make it more accessible to a broader audience. In this paper, we have attempted to fill this gap by introducing several examples to illustrate the main concepts and justify their relevance when approaching sustainability issues. Finally, we hope that MuSIASEM may come to represent the kind of special sunglasses described in Carpenter's movie, to be used to obtain better perceptions and representations of our sustainability predicament and for a sober discussion of radical imaginaries of change.

Acknowledgements: The authors would like to thank Professor Mario Giampietro for his invaluable comments on an earlier version of this paper and the IASTE research colleagues (www.iaste.info) for the insightful discussions around MuSIASEM. We also thank the anonymous reviewers for their helpful input. Any shortcomings are exclusively the authors' responsibility.

Funding: J.J. Larrabeiti-Rodríguez acknowledges the Government of Andorra for a predoctoral grant, ATC022-AND-Year 2020. Raúl Velasco-Fernández acknowledges the financial support from the Spanish

Ministry of Science and Innovation, the "María de Maeztu" Programme for Units of Excellence (CEX2019-000940-M) and from the University of Andorra through its doctorate program.

REFERENCES

Ahl, V. & Allen, T. F. H. (1996). *Hierarchy Theory*. Columbia University Press.

Ahmed, N., Marriott, A., Dabi, N., Lowthers, M., Lawson, M. & Mugehera, L. (2022). *Inequality Kills: The unparalleled action needed to combat unprecedented inequality in the wake of COVID-19*. https://doi.org/10.21201/2022.8465

Allen, T. F. H. & Giampietro, M. (2014). Holons, creaons, genons, environs, in hierarchy theory: Where we have gone. *Ecological Modelling*, *293*, 31–41. https://doi.org/10.1016/J.ECOLMODEL.2014.06.017

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

Barbieri, M. (2019). Code Biology, Peircean Biosemiotics, and Rosen's Relational Biology. *Biological 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.

Cabello, V., Renner, A., & Giampietro, M. (2019). Relational analysis of the resource nexus in arid land crop production. *Advances in Water Resources*, 130(January), 258–269. https://doi.org/10.1016/j.advwatres.2019.06.014

Cadillo-Benalcazar, J.J., Giampietro, M., Bukkens, S. G. F. & Strand, R. (2020). Multi-scale integrated evaluation of the sustainability of large-scale use of alternative feeds in salmon aquaculture. *Journal Of Cleaner Production*, *248*, 119211. https://doi.org/10.1016/j.clepro.2019.119210

Cadillo-Benalcazar, J.J., Renner, A. & Giampietro, M. (2020). A multiscale integrated analysis of the factors characterizing the sustainability of food systems in Europe. *Journal of Environmental Management*, *271*, 110944. https://doi.org/10.1016/j.jenvman.2020.110944

Cadillo-Benalcazar, J.J. & Renner, A. (2020). *Top-down and bottom-up vegetal and animal product metabolic profiles for 29 European countries (EU27 + United Kingdom + Norway) [dataset] [www document]*. Zenodo. https://doi.org/10.5281/ZENODO.3923010

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

Carpenter, J. (1988). *They live*. Universal Pictures.

Cilliers, P. (1998). *Complexity and postmodernism: Understanding complex systems*. Routledge.

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

Couix, Q. (2019). Natural resources in the theory of production: the Georgescu-Roegen/Daly versus Solow/Stiglitz controversy. *The European Journal of the History of Economic Thought*, *26*(6), 1341–1378. https://doi.org/10.1080/09672567.2019.1679210

Daly, H. (2005). Economics in a full world. *Scientific American*, *293*, 78–85.

Di Felice, L. J. (2020). *Energy systems as holarchies: Complexity and sustainability across scales [dataset] [www document]*. Zenodo. https://doi.org/http://doi.org/10.5281/zenodo.4271325

Di Felice, L. J., Cabello, V., Ripa, M. & Madrid-Lopez, C. (2021). Quantitative Storytelling: Science, Narratives, and Uncertainty in Nexus Innovations: *Science, Technology & Human Values*. https://doi.org/10.1177/01622439211053819

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

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

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

Fischer-Kowalski, M. (1998). Society's Metabolism: The Intellectual History of Material Flow Analysis, Part 1, 1860-1970. *Journal of Industrial Ecology*, *2*(I), 61–78. https://doi.org/10.1162/jiec.1998.2.1.61

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

Funtowicz, S. & Ravetz, J. (1993). Science for the post-normal age. *Futures*, *25*(7), 735–755.

Gell-Mann, M. (1994). *The Quark and the Jaguar*. Freeman.

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

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. *Ecological Economics*, *144*, 186–194. https://doi.org/10.1016/j.ecolecon.2017.08.012

Giampietro, M. (1994). Using hierarchy theory to explore the concept of sustainable development. *Futures*, *26*(6), 616–625. https://doi.org/10.1016/0016-3287(94)90033-7

Giampietro, M. (2003). Multi-Scale Integrated Analysis of Agro-ecosystems. CRC Press.

Giampietro, M. (2018). Perception and representation of the resource nexus at the interface between society and the natural environment. Sustainability (Switzerland), 10(7), 2545. https://doi.org/10.3390/su10072545

Giampietro, M. (2019a). On the Circular Bioeconomy and Decoupling: Implications for Sustainable Growth. *Ecological Economics*, *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. [www document] Available online:* https://magic-nexus.eu/documents/quality-scientific-advice-policy-insights-complexity

Giampietro, M., Allen, T. F. H. & Mayumi, K. (2006). The epistemological predicament associated with purposive quantitative analysis. *Ecological Complexity*, *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.

Giampietro, M., & Bukkens, S. G. F. (2015). Quality assurance of knowledge claims in governance for sustainability: Transcending the duality of passion vs. reason. *International Journal of Sustainable Development*, *18*(4), 282–309. https://doi.org/10.1504/IJSD.2015.072662

Giampietro, M. & Bukkens, S.G.F. (2022). Knowledge claims in European Union energy policies: Unknown knows and uncomfortable awareness. *Energy Research & Social Science*, *91*(102739). https://doi.org/10.1016/j.erss.2022.102739

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. [www document] Available online:* 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 the circular economy. *Environmental Science and Policy*, *109*, 64–72. https://doi.org/10.1016/j.envsci.2020.04.012

Giampietro, M. & Mayumi, K. (2000a). Multiple-scale integrated assessment of societal metabolism: introducing the approach. *Population and Environment*, *22*, 109–153. https://doi.org/10.1023/A:1026691623300

Giampietro, M. & Mayumi, K. (2000b). Multiple-scale integrated assessments of societal metabolism: Integrating biophysical and economic representations across scales. *Population and Environment*, *22*, 155–210. https://doi.org/10.1023/A:1026643707370

Giampietro, M. & Mayumi, K. (2008). The Jevons Paradox: The Evolution of Complex Adaptive Systems and the Challenge for Scientific Analysis. In J. M. Polimeni, K. Mayumi, M. Giampietro & B. Alcott (Eds.), *The Jevons Paradox and the Myth of Resource Efficiency Improvements* (p. 200). Earthscan Research Edition.

Giampietro, M. & Mayumi, K. (2018). Unravelling the complexity of the Jevons Paradox: The link between innovation, efficiency, and sustainability. *Frontiers in Energy Research*, *6*(APR), 1–13. https://doi.org/10.3389/fenrg.2018.00026

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

Giampietro, M., Mayumi, K. & Sorman, A. H. (2013). *Energy Analysis for a Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism*. Routledge. 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 *et al.* (Ed.), *Unifying Themes in Complex Systems X: Proceedings of the Tenth International Conference on Complex Systems*. Springer (Series: Springer Proceedings in Complexity).

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., Guzmán Casado, G. I., 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.

González de Molina, M. & Toledo, V. M. (2014). *The Social Metabolism. A Socio-Ecological Theory of Historical Change.* Springer International Publishing. 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. *Nature Sustainability*, *2*(3), 173–184. https://doi.org/10.1038/s41893-019-0225-2

Heinberg, R. (2007). *Peak everything: walking up to the century of declines*. New Society Publishers.

Holland, J. H. (1995). *Hidden Order: How Adaptation Builds Complexity.* Perseus Books.

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

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.

Infante Amate, J., González de Molina, M. & Toledo, V. M. (2017). El metabolismo social. Historia, métodos y principales aportaciones. *Revista Iberoamericana de Economía Ecológica*, *27*, 130–152.

Jasanoff, S. & Kim, S. H. (2015). *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power*. University of Chicago Press. https://doi.org/10.7208/9780226276663

Koestler, A. (1967). *The Ghost in the Machine*. Macmillan Co.

Kull, K., Deacon, T., Emmeche, C., Hoffmeyer, J. & Stjernfelt, F. (2009). Theses on biosemiotics: Prolegomena to a theoretical biology. *Biological 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. *Environmental Communication: A Journal Of Nature and Culture.*, *4*(1), 70–81. https://doi.org/10.1080/17524030903529749.

Lotka, A. J. (1922). Contribution to the energetics of evolution. *Proceedings of the National Academy of Sciences*, *8*(6), 147–151. https://doi.org/10.1073/pnas.8.6.147.

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

Luhmann, N. (1995). *Social Systems*. Stanford University Press.

Manfroni, M., Bukkens, S. G. F., & Giampietro, M. (2021). The declining performance of the oil sector: Implications for global climate change mitigation. *Applied Energy*, *298*, 117210. https://doi.org/10.1016/j.apenergy.2021.117210

Manfroni, M., Velasco-Fernández, R., Pérez-Sánchez, L., Bukkens, S. G. F. & Giampietro, M. (2021). The profile of time allocation in the metabolic pattern of society: An internal biophysical limit to economic growth. *Ecological Economics*, *190*, 107183. https://doi.org/10.1016/J.ECOLECON.2021.107183

Marcos-Valls, A., Kovacic, Z., Giampietro, M., Kallis, G. & Rieradevall, J. (2020). Isolated yet open: A metabolic analysis of Menorca. *Science of the Total Environment*, *738*, 139221. https://doi.org/10.1016/j.scitotenv.2020.139221

Marmot, M. G. (2004). Evidence based policy or policy based evidence? *BMJ*, *329*, 906–907. https://doi.org/10.1136/bmj.328.7445.906

Martinez-Alier, J., Munda, G. & O'Neill, J. (1998). Weak comparability of values as a foundation for Ecological Economics. *Ecological Economics*, *26*(3), 277–286.

McKinnon, A. (2010). Energy and society: Herbert Spencer's "energetic sociology" of social evolution and beyond. *Journal of Classical Sociology*, *10*(4), 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. *Ecological Economics*, *169*, 106567. https://doi.org/10.1016/j.ecolecon.2019.106567

Munda, G. (2008). *Social Multi-Criteria Evaluation for a Sustainable Economy.* Springer.

Nicolis, G. & Prigogine, I. (1977). *Self-Organization in Nonequilibrium Systems*. Wiley.

Odum, H. T. (1971). *Environment, Power and Society*. Wiley-Interscience.

Parra, R., Bukkens, S. G. F., & Giampietro, M. (2020). Exploration of the environmental implications of ageing conventional oil reserves with relational analysis. *Science of the Total Environment*, *749*, 142371. https://doi.org/10.1016/j.scitotenv.2020.142371

Pattee, H. H. (1995). Evolving self-reference: Matter, symbols and semantic closure. *Communication and Cognition-Artificial Intelligence*, *12*((1-2)), 9–27.

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. (2021). The international division of labor and embodied working time in trade for the US, the EU and China. *Ecological Economics*, *180*, 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*(7). https://doi.org/10.3390/su11072001

Prigogine, I. (1961). *Introduction to thermodynamics of irreversible processes*. Interscience Publishers.

Prigogine, I. & Glansdorff, P. (1971). *Thermodynamic Theory of Structure, Stability and Fluctuation*. Wiley.

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. *Economy and Society*, *41*(1), 107–125. https://doi.org/10.1080/03085147.2011.637335.

Renner, A., Cadillo-Benalcazar, J. J., Benini, L. & Giampietro, M. (2020). Environmental pressure of the European agricultural system: Anticipating the biophysical consequences of internalization. *Ecosystem Services*, *46*, 101195. https://doi.org/10.1016/j.ecoser.2020.101195

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

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 Sciences*, 4, 155–169. https://doi.org/10.1007/BF01405730

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E., Lenton, T. M., Scheffer, M. & Folke, C. (2009). Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society*, *14*(2). https://doi.org/10.5751/ES-03180-140232

Rosen, R. (2000). *Essays on Life Itself*. Columbia University Press.

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

Schrödinger, E. (1967). *What is Life? Mind and Matter*. Cambridge University Press.

Scott, I., & Gong, T. (2021). Coordinating government silos: challenges and opportunities. *Global Public Policy and Governance*, *1*(1), 20–38. https://doi.org/10.1007/s43508-021-00004-z

Shove, E., Pantzar, M. & Watson, M. (2012). *The dynamics of social practice : everyday life and how it changes*. SAGE.

Simon, H. A. (1962). The Architecture of Complexity: Hierarchic Systems. *Proceedings of the American Philosophy Society*, *106*(6), 467–482. https://doi.org/10.2307/985254

Spash, C. L. (2015). The content, direction and philosophy of ecological economics. In Martinez-Alier, J. & Muradian, R. (Eds.), *Handbook of Ecological Economics* (pp. 26–47). Edward Elgar. https://doi.org/10.4337/9781783471416.00006

Spash, C. L. (2020). A tale of three paradigms: Realising the revolutionary potential of ecological economics. *Ecological Economics*, *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 Economics Review*, *19*(87), 221-229. Available online: http://www.paecon.net/PAEReview/issue87/SpashSmith87.pdf

Strassheim, H. & Kettunen, P. (2014). When does evidence-based policy turn into policy-based evidence? Configurations, contexts and mechanisms. *Evidence & Policy: A Journal of Research, Debate and Practice*, *10*(2), 259–277. https://doi.org/10.1332/174426514X13990433991320

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

Velasco-Fernández, R., Dunlop, T. & Giampietro, M. (2020). 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., Pérez-Sánchez, L., Chen, L. & Giampietro, M. (2020). A becoming China and the assisted maturity of the EU: Assessing the factors determining their energy metabolic patterns. *Energy Strategy Reviews*, *32*, 100562. https://doi.org/10.1016/j.esr.2020.100562

Weitz, N., Carlsen, H., Nilsson, M. & Skånberg, K. (2018). Towards systemic and contextual priority setting for implementing the 2030 agenda. *Sustainability Science*, *13*(2), 531–548. https://doi.org/10.1007/s11625-017-0470-0

White, L. A. (1943). Energy and evolution of culture. *American Anthropologist*, *14*, 335–356.

Wiedmann, T., Lenzen, M., Keyßer, L. T. & Steinberger, J. K. (2020). Scientists' warning on affluence. *Nature Communications*, *3107*. https://doi.org/10.1038/s41467-020-16941-y

Zipf, G. K. (1941). *National Unity and Disunity: The Nation as a Biosocial Organism*. Principia Press.

ACERCA DE LOS AUTORES

JUAN JESÚS LARRABEITI-RODRÍGUEZ

Master in Environmental Studies (ICTA-UAB). He is currently a PhD candidate at the University of Andorra. His research focuses on studying societal metabolism within the ecological economics framework from a biophysical and multiscale approach. More specifically, his research analyses the water-energy-food nexus of a country with high tourism specialization, such as Andorra, using the MuSIASEM approach. He is also interested in environmental and sustainability policy analysis focusing mainly on semiotic and ethical issues, i.e. reflecting on how dominant narratives and imaginaries are causing environmental degradation.

RAÚL VELASCO-FERNÁNDEZ

PhD in Environmental Science and Technology (ICTA-UAB). He is currently a postdoctoral researcher at ICTA. His research focuses on the systemic relations between energy, labour, materials, and economic development. In more technical terms, that is the study of societal metabolism from a biophysical and multiscale perspective based on biophysical economics, complex system theory and social practices. During the last years, he has developed different analytical tools within the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) accounting framework, such as the End-Use Matrix, and applied these to different case studies (China, the EU, USA and India). He is also interested in analysing wicked sustainability problems and developing tools to analyse the metabolic patterns of non-commodified human activities.