MuSIASEM framework testing from a System Dynamics perspective

Implications for a sustainability assessment

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Contents

Abstract

The current work is a theory-oriented research that tries to address a theoretical discussion on sustainability analysis of complex systems by using SD methodology and MuSIASEM in an evaluative exercise. MuSIASEM as one of the latest frameworks developed for a bio-economic analysis is tested using SD methodology in order to assess its applicability for dynamic systems analysis. Three modeling exercise were performed under MuSIASEM theoretical guidance and following SD principles. An appraisal of the compatibility and feedback learning of the combination of both is developed in the light of further energy studies for sustainability, having special focus on the dynamic component of any sustainability assessment.

Key words: sustainability, energy analysis, system dynamics, bio-economic assessment, MuSIASEM

Chapter 1

Introduction

The acknowledgment of biophysical limits is fundamental to understand how socio-ecological systems work, for risk avoidance and sustainability applications. Although these concerns are not new (i.e. Vernadskii 1826; Meadows, Randers & Meadows, 1972) the dominant scientific narratives, mainly economic, for decades have reproduced a paradigm that neglects feedback processes between institutional systems and nature.

One of the latest frameworks developed for a bio-economic analysis is the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM). This approach explains how it is possible to study the feasibility, viability and desirability of transitions (adjustments) to what they call the "*societal metabolism pattern*" of a society given the interconnected dynamics between societal functions, standards of living, population size, energy use, natural funds, among many other factors.

The validity of a scientific framework is an important condition for its usefulness. This research project is dedicated to testing the validity of MuSIASEM from a System Dynamics (SD) perspective, in the light of possible applications for sustainability assessments.

The organization of the chapters is the following: Chapter 1 contains the introduction, purpose of the research, research objective and research questions. Chapter 2 briefly reviews the challenges of energy analysis, sustainability assessments for socio-ecological systems, plus the use implications for MuSIASEM and SD. Chapter 3 will be dedicated to the explanation of the MuSIASEM framework. Chapter 4 contains the results and explanation of the first modeling exercise developed in order to test the framework from an SD perspective. This modeling exercise corresponds to an analysis on the energy use of Argentina from 1990-2007, developed using MuSIASEM and published in the international journal *Energy* in 2011.

Chapter 5 contains two other modeling exercises developed with synthetic data on key points addressed by MuSIASEM. This time, the modeling exercises were guided directly by the literature outlining the framework. The modeling process results, and the critical points of the structural and behavior tests developed to make these exercises, are explained.

Chapter 6 contains reflections on the validity of MuSIASEM from a SD perspective and as a sustainability assessment framework, whether MuSIASEM and SD can be compatible according to SD principles, how SD can improve the understanding of an integrative systemic analysis for sustainability, SD proposals to MuSIASEM's "sustainability checks" and the constrains of both frameworks.

Chapter 7 has conclusions on the relevance of MuSIASEM in regard to its current applications, a critical appraisal of MuSIASEM as a narrative for sustainability, its capacity to be used to build models and replicate results from its applications, proposals for the further development of MuSIASEM attained using SD methodology in order to overcome specific limitations, and agenda for further research.

Purpose of the research

Current world problems are a result of a complex interconnected network of different natural and human-created processes. New scientific narratives and tools are required to integrate system understanding in a coherent way system and make strategic actions. MuSIASEM was only recently developed, but is already considered by scientific journals, governments and international organizations[1] as a way to develop energy analyses and sustainability assessments that link the internal and external constrains of the system to which human society belongs to. On the other hand, it has been claimed that SD methodology has the capacity to aid the decision-making processes within dynamic systems, by improving system understanding through simulation research that provides for the development and testing of policies. Both seem promising for sustainability assessments and proposals for practical solutions.

The current work is theory-oriented research that tries to address the theoretical discussion of 'sustainability analysis of complex systems' by using SD methodology and MuSIASEM in an evaluative exercise. An appraisal of the compatibility and feedback learning of a combination of both is sought in the light of further energy studies for sustainability, having a special focus on the dynamic component of any sustainability assessment.

Research objective

Test the validity of MuSIASEM to the extent that it provides a consistent systemic view applicable for dynamic systems analysis, from a SD perspective, and find out whether SD can improve its approach to sustainability assessments.

For this purpose, a study of MuSIASEM's qualitative and quantitative components was required in order to examine it as a narrative and analysis method able to sustain[2] the conceptualization, characterization and formulation stage of a SD model. The three modeling exercises performed to test MuSIASEM are the following:

> a) Argentina's energy use from 1990 to 2007. This modeling exercise and the data required was based on the study of an application case of the MuSIASEM methodology contained in the article published in the international journal Energy "*Going beyond energy intensity to understand the energy metabolism of nations: The case of Argentina" by Marina Recalde and Jesus Ramos Martin (2011)*
>
> b) Human Activity and Dynamic Energy budget models. The model building process was mainly based from the literature of the book *"Energy Analysis for a Sustainable Future: Multi-scale integrated analysis of societal and ecosystem metabolism" (Giampietro et al. 2013)* and the publication by the Food and Agriculture Organization from United Nations *"An Innovative Accounting Framework for the Food-Energy-Water Nexus*: *Application of the MuSIASEM approach to three case studies*" published on October 2013. These two modeling exercises were performed on the key issues addressed by MuSIASEM. Synthetic data was used to run the models.

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[1] MuSIASEM has been recently used by international entities such as the Food and Agriculture Organization of United Nations, Ecuadors' government and the Research Centre Institute for Environment and Sustainability from the European Comission as a tool to improve public policy. It has also provided content to several book publications and articles in scientific journals such as *Energy* on the framework and its applications.

[2] Sustain, interpreted as: give support and meaning to a process or action.

The analysis of these modeling exercises from a SD perspective will be grounded on the following tests: 1) Structure test: boundary and snapshots in order to evaluate the congruence of MuSIASEM as a framework for system analysis with SD models and gain SD insights. 2) Behavior test: in order to test the logical behavior of the model developed and the coherence of the results with what the framework is claiming to analyze for a sustainability assessment.

Research questions

1) Is MUSIASEM a framework able to sustain SD modeling exercises? What are the compatibilities and incompatibilities between both?

2) What are the possibilities of SD improvements to MuSIASEM for sustainability assessments from a dynamic perspective?

Research strategy and analysis procedure

Case study with inductive approach and documentary analysis

As long as the goal of the current project is to analyze the validity of MuSIASEM from a SD perspective, this research possesses a strong explanatory character. In order to analyze its validity, it is fundamental to understand integrally the way MuSIASEM is written as a narrative, its tools and its purpose. This will be only provided through the scrutiny of the literature published on the framework. The method used to analyze its validity will be System Dynamics, which provides qualitative and quantitative components to the analysis especially at the moment of performing the model building exercises; therefore, the present research project has a mixed method approach, qualitative and quantitative, in order to get a more complete understanding on a pragmatic knowledge claim case.

There are two main types of information required:

1) Secondary sources, text material sources, especially text from scientific journals and books. The secondary data will be gathered through documentary, archival and electronic research.

The main literature revised to study MuSIASEM were the following:

- ✓ Giampietro, M. et al. (2013). Energy Analysis for a Sustainable Future: Multi-scale integrated analysis of societal and ecosystem metabolism. Routledge.
- ✓ Giampietro, M. et al. (2012). The Metabolic Pattern of Societies: Where Economists Fall Short. Routledge.
- ✓ Sorman A.H. & Giampietro, M. (2013). The energetic metabolism of societies and the degrowth paradigm: analyzing biophysical constraints and realities. Journal of Cleaner Production, 38:80-93.
- ✓ Giampietro, M. & Mayumi, K. (2000). Multiple-scales integrated assessments of societal metabolism: Integrating biophysical and economic representations across scales. Population and Environment 22 (2): 155-210

Regarding the SD literature, some sources studied for this research belong to literature on validation testing in modeling exercises and on the critical use of SD as a perspective of analysis:

- ✓ Meadows, D. H. & Robinson, J. (1985). “The Electronic Oracle: Computer Models and Social Decisions. John Wiley & Sons, Chichester.
- ✓ Meadows, D. H. (1979). “The unavoidable a priori,” Elements of the System Dynamics Method, ed. J. Randers, MIT Press, Cambridge MA.
- ✓ Zock, A. (2004). “A critical review of the use of systems dynamics for organizational consultation projects”. Deustche Lufthansa.AG, Future European operations, Ground and Inflight Processes, Lufhansa Basis, Pp. 1-29
- ✓ Barlas, Y. (1989) Multiple tests for validation of system dynamics type of simulation models. European Journal of Operational Research 42: 59-87

On Sustainability and Complex system some of the literature revised is the following:

- ✓ Constanza et al. (1993). ”Modeling Complex Ecological Economic Systems” American Institute of Biological Sciences Stable, BioScience Vol. 43(8): 545-555
- ✓ Daly, H. (1990). “Toward some operational principles of sustainable development”. Ecological Economics 2:1–6.
- ✓ Goodland, R. (1995). The concept of environmental sustainability. Annu Rev. Ecol Syst 1995 (26):1-24
- ✓ MEADOWS (1998). “Indicators and Information Systems for sustainable development”. A Report to Balloton Group.

2) The information to run the first simulation exercise corresponds to the information provided in the referenced article from which the analysis was based. The other two simulation models required synthetic data for two reasons a) being that no dynamic model has been developed using MuSIASEM and no application case that could provide enough data to compare was available b) the purpose of the modeling exercises are to test the validity of the framework from a SD perspective, therefore the explanatory capacity of how MuSIASEM works and whether it can sustain a modeling exercise is what is sought.

Chapter 2

Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) framework and System Dynamics (SD) Methodology implications for a sustainability assessment

"Complexity also depends on the question you ask"
Timothy Allen[3]

[3] Professor of Botany and Environmental Studies from Wisconsin University. Leader in the fields of hierarchy theory, systems theory, and complexity.

Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) framework and System Dynamics (SD) Methodology implications for a sustainability assessment

Complex systems and sustainability

The acknowledgment of biophysical limits is fundamental to understand how socio-ecological systems work, for risk avoidance and sustainability applications. Although these concerns are not new (i.e. Vernadskii 1826; Meadows, Randers & Meadows, 1972) the dominant scientific narratives, mainly economic, for decades have reproduced a paradigm that neglects feedback processes between institutional systems and nature.

Folke et al. (2002) points out two fundamental errors when dealing with environmental issues. The first is the consideration of linear, predictable and controllable ecosystem responses to human action, second, the idea that human and ecosystem spheres can be treated separately. The conceptual integration of natural and social systems is called socio-ecological systems. These systems act in non-linear ways, are strongly coupled and possess thresholds in their dynamics. Different kinds of elements (biophysical, social, economic, geographic, cultural) have to be considered for the analysis of these systems.

Dennis Meadows stated in 2012 during the conference "*Is it too late for sustainable development*?" organized by New Economic Thinking Institute at Oxford University that there are more than 100 definitions of sustainability, which makes the concept meaningless. He specifically critiques assessments for sustainability based solely on economics. Since the characteristics of ecological system cannot be explained and studied just by monetary evaluations, a biophysical analysis is needed instead. Ecological economics came to be a new branch under which this complementary study could be done. For example, Daly's (1990) definition of sustainability it is based on a biophysical perspective of 3 different things: i) renewable resources: the rate of harvest should not exceed the rate of regeneration, 2) pollution: the rate of waste generation should not exceed the assimilative capacity and 3) nonrenewable resources: their depletion should require comparable development of renewable substitutes for those nonrenewable resources. Goodland (1995) divides sustainability into three main dimensions: economic, social and environmental, he considered a sustainable state without the integration of these dimensions could not be reached. Nevertheless, this three-category division exemplifies the bounded disciplines from where decisions and policies are made. Several authors divide sustainability into two visions i) the weak sustainability paradigm: where it is considered that human capital can replace ecological services and natural resources and ii) the strong sustainability paradigm that considers environment, nature and its ecological functions cannot be reproduced by mankind's industrial or other processes (Ayres et al. 1998., Martinez- Allier, 1995., Turner, 1992.,). Specifically, primary energy sources cannot be reproduced according to thermodynamic laws, i.e., the cycle of water cannot be controlled by human technology (controlling around 16 terawatts of energy) because it uses 35,000 – 44,000 terawatts of solar energy (Giampietro et al., 2011).

Costanza (2012) states a comprehensive understanding of linked systems requires the synthesis and integration of several different conceptual frameworks. Former definitions are already expressing a notion of sustainability that has to deal with the complexity of the nature processes linked to human intervention in a determined space. The complexity notion emerged in the 60s, and it refers to a condition where there are multiple connections among different scales or hierarchies in a system, sharing at the same time, feedback processes of elements within scales, structure driven pattern emergence and unpredictable change regarding initial conditions (Waldrop, 1992., Allen, 1996., Koestler, 1967., Prigogine, 1972) . Constanza (2002) adds the feedback loops in complex systems makes it hard to distinguish cause from effect, space and time lags, discontinuities and limits. Thus, this results in it being very hard to keep track of all interactions, find appropriate ways to measure it and even more, plan solutions with appropriate risk or impact assessments, especially with regard to sustainability. Therefore, a previous step required to find integrative tools to deal with reality is mentioned by Allen (2013), called *qualitative change*, referring to the challenges of creating a narrative that expresses system understanding, meaning a coherent multidisciplinary explanation of phenomena.

Data and information are needed to produce policies and solution. In the quest to measure data and produce useful information it is necessary i) the selection of what is relevant and what is not according to a sound integration of the different parts of the system and ii) a coherent system understanding valid at the individual and general level, these are conditions also necessary to select a narrative or even the narrative sought to be developed. Constanza et al. (1993) also alerts that in the quest to produce information from the aggregated and interactive scales in order to arrive at results splitting reality into single elements of isolated parts, i.e. making subdivisions of the universe and the components of it, in order to make the job easy, there is a risk of missing the main interaction processes of the economic and ecological system. He attributes this is a common fact in classical scientific disciplines and argues complex systems cannot be treated by such approaches because they are insufficient in providing an understanding on them. Moreover, ignoring these interconnections leads to misperceptions of the system and unavoidable policy failures (Constanza, 1987., Folke et al. 2002).

"*What gets measured, gets managed*." Peter Drucker

Socio-ecological models in the quest for practical solutions

Socio-ecological systems management is a difficult task because the challenges inherent in the characterization process, as we have discussed, are highly complex. They keep you tied to the uncertainty of outcomes of any intervention, even without one. In order to select the best strategy to deal with a problem or project, the post-normal science paradigm has established two attributes; one of them is the decision stakes, and the other is the level of uncertainty, which refers to inadequate information as the source of this inexactness, unreliability, and border with ignorance (Walker et al. 2002). Nevertheless, it can be the case that even with plenty of information there is a high

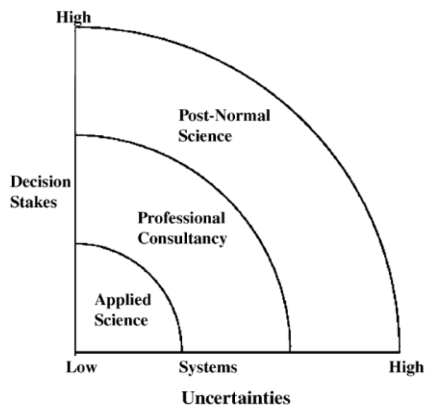


Fig. 1 – The Post-Normal Science diagram.

Figur 1 The Postnormal science paradigm (Ravetz 2007)

uncertainty due to a lack of system understanding. When both uncertainty and decision stakes are high the problem solving strategy of traditional scientific and reductionist narratives will be insufficient and the best strategy to select lies within the post-normal science approach (Funtowicz & Ravetz 1994).

Management of complex systems demands practical information and tools, complex systems are dynamic, i.e., they are in constant change not static, and possess nonlinear relations. Therefore, the analytical methods they require in order to be explained possess a higher degree of difficulty according to the increase in size of the boundaries selection, relations identified between elements and their feedback processes, among other issues. In the next chart we can observe the difficulty of the solving process of a system according to its number of equations and the nature of the dynamics between the system elements (linear or not linear).

Table 1. The limits of analytical methods in solving mathematical problems (after von Bertalanffy 1968). The thick solid line divides the range of problems that are solvable with analytical methods from those that are difficult or impossible using analytical methods and require numerical methods and computers to solve. Systems problems are typically nonlinear and fall in the range that requires numerical methods. It should be noted that whereas some special problems that fall in the areas labeled impossible in the table are actually possible to solve using analytical methods (frequently requiring special tricks), in general one cannot depend on a solution being available. Computers have guaranteed that a solution can be found in all the cases listed in the table.

	Linear			Nonlinear		
Equations	One equation	Several equations	Many equations	One equation	Several equations	Many equations
Algebraic	Trivial	Easy	Difficult	Very difficult	Very difficult	Impossible
Ordinary differential	Easy	Difficult	Essentially impossible	Very difficult	Impossible	Impossible
Partial differential	Difficult	Essentially impossible	Impossible	Impossible	Impossible	Impossible

Figur 2 **Extracted from Constanza (1993) "Modeling complex ecological economics systems". BioScience 48(3):3**

Computer software programs for modeling have come to bring tools to deal with the complexity of systems, providing the capacity of tracking nonlinear effects of one element over another in a broader chain happening consecutively or simultaneously even within different scales of the system according to the boundary definition selected by the observer. Computer modeling, beyond a tool of certainty and control, is also considered as an aid for social exploration and design, consistently with the conception of simulation research as a tool for the practice of the scientific method *(Meadows, 2002).*

Following this idea of Meadows, computer-modeling activities can work as a social exploration and design tool through the iterative process of simulation research. The next diagram extracted from Zock (2004) shows how the whole modeling process from the system conceptualization stage to the simulation stage helps to get a better understanding of the system. The simulation also aids the system conceptualization stage, which improves the model formulation and then again the simulation. This increasing the likelihood of performing a good policy analysis, along with improved support and implementation processes.

Among the diverse applications of computer simulation modeling, ecological modeling for management issues and strategic interventions are becoming ever more common. Specifically, SD models are expected to be helpful in designing organizational interventions, to explore and make evaluations, and to find the most adequate actions as solutions for problems. When the model building process is related to implementation plans in organizations, it is applied as a tool for "action research", improving the scientific analysis of different sizes of complex systems or organizations, while at the same time giving practical possibilities of application (Milling, 2007).

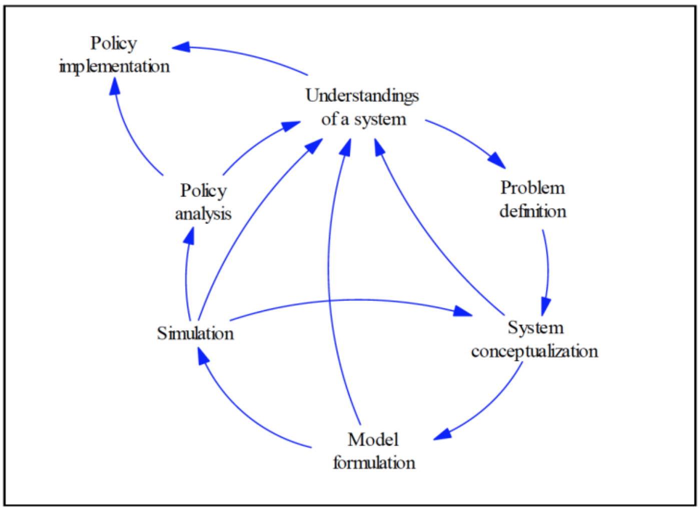


Figure 1: Seven step modeling process (Start: Problem definition) proposed by Richardson and Pugh (taken from Richardson and Pugh, 1981).

Figur 3 from Zock (2004). "A critical review of the use of systems dynamics for organizational consultation projects". Pp. 6.

Some characteristics of complex social systems have been identified after the application of SD principles to the study of some organizations, for example, the ones stated by George Richardson in his paper "*Feedback thought in the social Sciences and Systems Theory* " referred by Zock (2004):

- ✓ Complex systems are remarkably insensitive to changes in many system parameters
- ✓ Complex systems counteract and compensate for externally applied corrective efforts
- ✓ Complex systems resist most policy changes
- ✓ Complex systems contain influential pressure points, often in unexpected places, from which forces will radiate to alter system balance
- ✓ Complex systems often react to a policy change in the long run in a way opposite to how hey react in the short run
- ✓ Complex social systems tend toward a condition of poor performance.

As we have seen, System Dynamic models have been lately used in socio-ecological systems modeling and they are considered also as a tool for understanding the configuration and functioning of complex systems. In the next sections some ideas on how, in theory, SD can be a suitable tool for energy analysis aims and their capacity to be applied in combination with integrative frameworks on the topic is presented.

Energy analysis complexity for a sustainability assessment

Current world energy issues are demanding more accurate and manageable ways of being accounted for. According to Giampietro et al. (2013) traditionally what is common to see in the national energy balance are statistics with dubious methods of aggregation that provoke misleading conclusions, therefore the ability to make informed decision with this information is limited. They also consider that the linear representation of energy flows going to different parts of society tend to miss autocatalytic loops of energy, meaning the loops that allow the reproduction of the system and take the system to different equilibrium states.

A systemic comprehension of energy transformation has to have defined boundaries regarding the time and space related to the type of energy being measured, and a pertinent scale of analysis, only in this way can a quantitative analysis can be performed. At the same time, it must have a qualitative component that supports a system conceptualization able to integrate the different scales or hierarchies of the energy conversion processes in a society.

However, it is rare to find such systemic approaches within the history of energy accounting because of the difficulty in finding an epistemology capable of addressing the difference between non-equivalent energy forms and the multiple scale issues for quantitative analysis (Giampietro et al., 2013).

One of the latest frameworks developed for a bio-economic energy analysis is MUSIASEM. This approach claims to make possible to study the feasibility, viability and desirability of the societal metabolic pattern of a society. According to Giampietro (2012) the societal metabolic pattern is given by the processes of energy and material transformation that society is consuming to continue its existence and functions at the current levels. Societal metabolism is also a notion used to assess the sustainability level of a society because the energy and material transformations tradeoffs, considered as resources needed for a society to keep living, are under specific biophysical conditions, i.e., a society cannot spend more than the biophysical capacity of its territory. The following ideas imply a large interconnected set of dynamics between societal functions, standards of living, population size, energy use and natural funds, among many others. MuSIASEM is composed of different tools in order to make a sustainability appraisal; those will be explained in the following chapter.

Before continuing, it is pertinent to explain some of the compatibilities that can be seen on first sight between MuSIASEM and SD methodology, which in turn motivated this research project.

MUSIASEM and SD as dialogic frameworks for modeling purposes

There are two important statements to consider when integrating two different frameworks in an evaluation exercise like the present work: according to Allen (2013), most scientific work is based on formulating models of phenomena. Nevertheless, the comprehension of the phenomena expressed through its narrative is essential to build those models. The validity of a scientific framework or narrative is an important condition for its usefulness and applicability. In addition, Meadows (1996) considers the paradigm or discipline of origin shapes the way the modeler or researcher sees the world.

At this point, we have three key issues that clarify the conditions of the analysis where this research is embedded. 1) The need of a good narrative on the phenomena: In order to produce models of the world in a coherent way, it is important to have a narrative capable of comprehending the phenomena to observe it in a proper way 2) The acknowledgment that this narrative is subject to the framework or discipline attachment while observing the world. 3) While evaluating the validity of a framework, theory or ideas, it is important to recognize that also the analysis method used to validate or discard it possess its own bias.

Supporting the arguments in favor of integrating disciplines or narratives, we found that complex systems have characteristics that are not suitable to reductionist approaches, for instance the conditions of unpredictability, path dependency and multi-scale organization. Regarding a sustainability analysis, the appropriation of a strong definition of sustainability implies a) consideration of biophysical matters within energy and economic analysis (Giampietro, 2013) and b) a systemic world view with all possible interactions captured, while maintaining an explicative capacity and relevance. At the moment of addressing these characteristics in complex system simulation exercises, we should consider the conditions Constanza recommends for models: realism, generality (robustness) and precision, conditions hard to achieve when referencing just a single discipline.

Any framework or methodology that intends to make a sustainability assessment of complex systems by using computer modeling tools must take into consideration three major independent categories which represent, at the same time, questions and opportunities while modeling complex ecological-economic systems, as addressed by Constanza (1993):

> a) **Application of the evolutionary paradigm** to modeling ecological economic systems: uncertainty, surprise, learning, path dependence, multiple equilibrium, suboptimal performance, lock-in, and thermodynamic constraints, specifically the applicability of thermodynamic principles. A key issue is the choice of measure or multiple-measures of performance of the system selection process to be observed.
>
> b) **Scale and hierarchy considerations**: definition on how hierarchical levels interact with each other and how to develop three basic methods of scaling for modeling ecological economics system, also to explore how the chaotic-systems dynamics and fractal theory can be applied in this area.
>
> c) **Nature and limits of predictability** in modeling ecological economic systems: nonlinearities raise the questions on the influence of resolution on the performance of models, specially predictability, modeling efforts have demonstrated that behavior or the system state is very sensitive, for instance, to the change of initial conditions. For this reason the need of better measures of model correspondence with reality and long term behavior is stressed. The criteria: generality, realism and precision, is proposed to be incorporated in the observations and measurement development.

As we can observe, for Constanza (1993), one of the three main opportunities in ecological economic systems modeling is the scale and hierarchy consideration where, as explained before, it is fundamental to define how levels interact with each other. Simulation research seems fit to explore the influence of scale, resolution and hierarchy definition on the behavior of the system.

Donella Meadows in her report “Indicators and Information Systems for sustainable development“ delivered to the Balaton group in 1998, develops suggestions for indicator processes and linkages and states that information system should be organized into hierarchies that increase the scale level and decrease specificity.

As we can observe, the scaling and hierarchy categorization, as well with the selection of the measurements units is fundamental in order to have a better analysis of complex system behavior and sustainability assessment. The next graphic shows some of the challenges for integrative scales assessments such as time horizon, narratives needed, energy types, ranges of values and factors relevant of each scale of analysis selected.

40 *Defining the problem*

Table 2.1 Examples of non-equivalent assessments of the energy equivalent of 1 hour of human labour found in scientific analyses

Level	*'Grain' and 'Time Horizon' of assessment*	*NARRATIVE*	*Range of values*	*Energy type*	*Factors affecting the assessment*
n+3 Gaia	Centuries Millennia	EMergy analysis of biogeochemical cycles and ecosystems	10–100 GJ	Embodied solar energy	• Ecosystem type • Choice in the representation • Transformities • Choice of ecological services included
n+1 society	1 decade 1 century	Societal metabolism	200–400 MJ	Oil equivalent	• Energy source mix • Energy carrier mix • End uses mix • Efficiency in energy uses • Level of technology • Level of capitalization
n household	1 year 1 decade	Time allocation Technological conversions	2.0–4.0 MJ 20–40MJ	Food energy Oil equivalent	• Quality of the diet • Convenience of food products • Food System characteristics
n-2 body/organs	1 hour 1 year	Physiology	0.2–2.0 MJ	ATP/food energy	• Body mass size • Activity patterns • Population structure (age and gender)

Figur 4 **Examples of non-equivalent assessments of the energy equivalent of 1 hours of human labor found in scientific analyses (from Giampietro et al., 2013: p.40).**

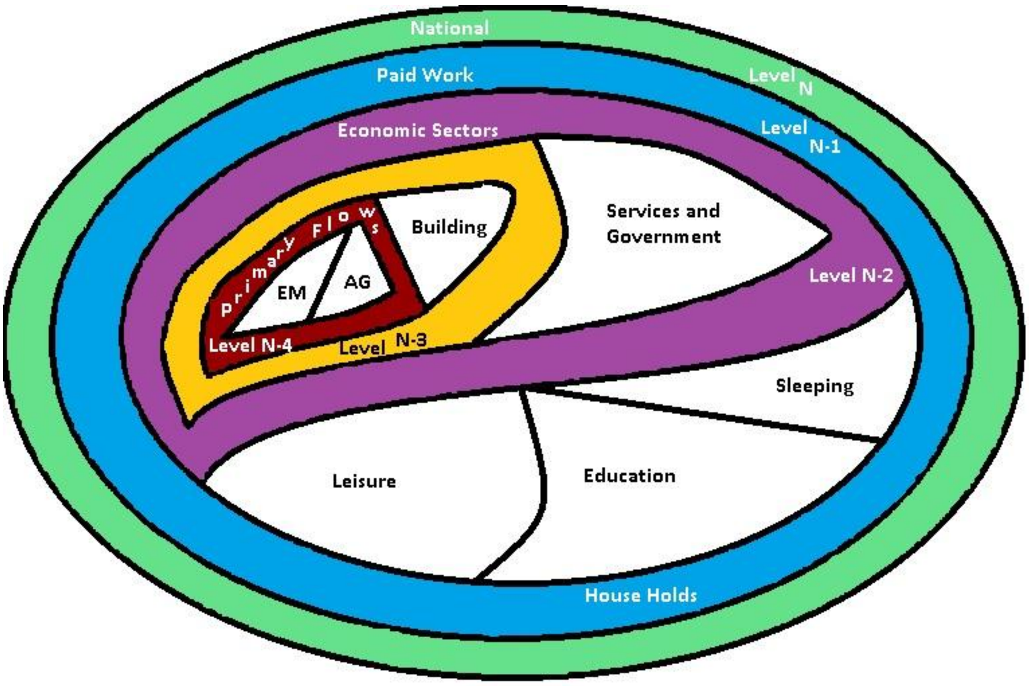
Giampietro et al. (2013) considers that if a more appropriate and useful energy analysis is to be developed based on a particular methodology, it must consider as crucial transparency regarding:

- ✓ Scaling assumptions linked to the narrative of energy transformation; this means coherency between the assumptions made based on the energy use process, that includes the definition of goals of the process, boundary conditions, initial conditions and time horizon
- ✓ Semantic choice of relevant energy forms with respective protocols of accounting for special cases
- ✓ Semantic choices related to the assessment of the quality of data
- ✓ Criteria to evaluate the usefulness and results of the analysis
- ✓ Choice of indicators and definition of their feasibility domain.

The integration of SD with MuSIASEM in a testing exercise responds to some conceptual similarities found in both, specifically to the recurrence to the endogenous point of view, fundamental in SD, and hierarchy and scaling considerations:

- The funds and flows consideration in its narrative coming from Georgescu-Roegen's model from which the categorization of the variables used in this analysis are derived. In SD, the existence of levels or stocks which are modified by flows of information or material over time under a certain system boundary is from where the dynamic behavior arises from, it is from the interaction of these stocks and flows in a certain space and given time from where the feedback loops take part in the system, generating the dynamic behavior (Richardson, 2011).

- MuSIASEM provides a form of accounting the societal energy requirement in different levels (national, economic level, households and specific sectors) grounded on a society's internal configuration (such as population composition or socio economic identity) regarding its functions, and on its external constraints (primary energy sources and natural resources availability). The closed boundary selection of the system implies the need for focusing the study on the structure driving the behavior of the energy and material flows and human activity required by that system. MuSIASEM also divides society in four different hierarchical levels, which have specific processes on the material, energy and human activity flows or allocation. Each level represents one boundary selection. The integration of levels must give place to the aggregated behavior of society. The sustainability analysis is based also on the congruence of the dynamics between each level, within the external constrains of the society as a whole.



Figur 5 Societal Levels according to MuSIASEM as an example of "holons" theory. Own Elaboration. Digital design by Yehia Mokhtar

- The consideration of the existence of a pattern of energy use in the society according to its structure and its recurrence to that pattern of MuSIASEM approach is based on the thermodynamic equilibrium state commonly used to explain characteristics of complex systems. It states that all systems tend to evolve characterized because within itself all the system properties are determined for intrinsic factors and not external influences, i.e., the equilibrium states are coherent with the system boundaries and the constrains to which it is subjected. If one part of these intrinsic factors resulted modified for any reason the system tend to show resilience capacity meaning it will tend to not move to another equilibrium state. Thermodynamic laws are applicable to the study of ecological economic systems (Eriksson, 1991). This could imply the existence of a balancing feedback loops in the system, but it can be also result of a emergent behavior or adaptation capacity driven by changes in the agents within the system which is out of the scope of SD methodology.

The former first sight findings on similarities and compatibilities of both perspectives and the theoretical match with key issues on socio-ecological system modeling motivate the study of MuSIASEM framework as a narrative and SD as a method of analysis at the time of studying society and energy issues for sustainability, attending as well the authors call for external disciplines scrutiny on the framework.

Chapter 3

MuSIASEM framework explanation

MuSIASEM framework explanation

The *Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism approach* (MuSIASEM) is one of the latest methodologies that provides basis to a bio-economic analysis and it proposes an integrative way of dealing with multiple scales by offering a characterization of each societal level (national, economic sectors and house holds) according to its matter and energy flows to analyze the feasibility and viability of the societal functions and ecosystem state.

Past applications of this methodology attempt to address the implications of demographic changes, peak-oil determining a declining supply of net energy sources (Giampietro et al. 2012; Sorman and Giampietro, 2010) and the effects of the Jevons' Paradox when considering evolutionary adjustments in the metabolic pattern of societies (Polimeni et al. 2008).

MuSIASEM was originally developed to achieve an analysis of the metabolic energy pattern of a society, but later applications have extended it to cover the energy-food-water nexus. Currently the Food and Agriculture Organization from United Nations is using it to develop a *Nexus Rapid Appraisal* to support governmental decision-making processes to evaluate the impacts of certain actions across levels and sectors of society.[4]

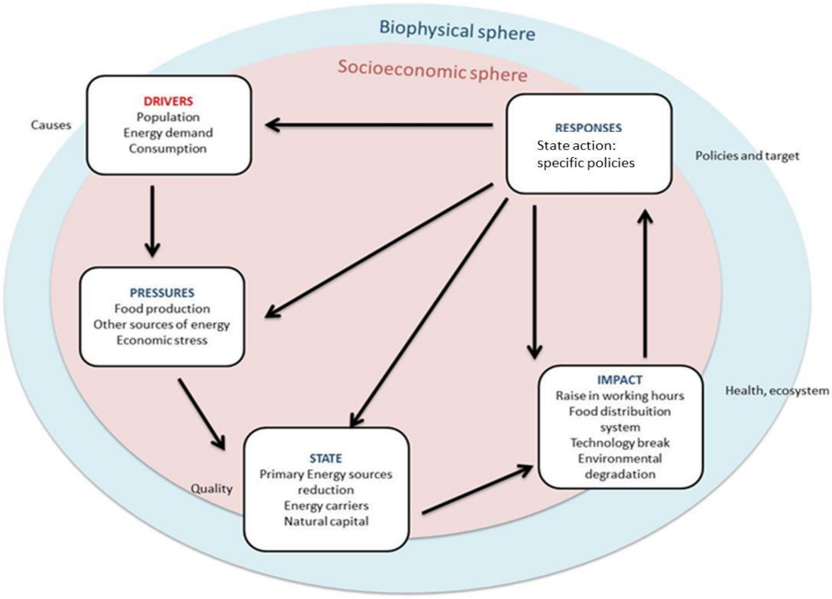
Societal metabolism definition

According to the main literature on the framework, the concept of societal metabolism establishes a link between *exosomatic* energy, which is metabolized by humans outside the human body, and the *endosomatic* energy, metabolized inside the human body (Georgescu-Roegen, 1971). This implies that the exosomatic metabolic pattern can be associated to forced relations between: (i) the amount of hours of human activity allocated to economic activities versus household sector (working hours versus non-paid work, leisure plus physiological overhead), and (ii) within the economy the amount of hours of human activity allocated to the different economic sectors (production of energy carriers, food, goods, transportation, and other basic societal services). The given profile of allocation of human activity across these different functions, reproducing humans in the household sector and reproducing the economic process in the economic sectors, is the result of a complex set of relations (productivity of labor in the various sector, that in turn is related to the amount of power capacity, level of technology and consumption of energy carriers used for the different tasks). A significant change in the profile of distribution of any one of these production factors (labor, power capacity, energy carriers) over the various compartment of the society may bring system instability. In relation to this point the MuSIASEM approach makes it possible to assess the *viability domain* of dynamic energy budgets associated with the metabolic pattern of a country.

An example of the biophysical and economic interrelations that this framework implies tried to be reflected in the next conceptual Model. In particular, the MuSIASEM makes it possible to study the feasibility, viability and desirability of transition (adjustment) to different values of the dynamic

[4] The Energy, food, water nexus. A water, food, energy nexus approach to inform Policy Making. Food and Agriculture Organization of Unites Nations, June 2014. Electronic source: http://www.fao.org/energy/81320/en/

energy budget obtained by using a different mix of Primary Energy Sources and a different mix of end uses in the various compartments of the society. As we can observe in the next diagram, biophysical and socioeconomic spheres are interrelated and in constant interaction, any change in the primary sources of energy will have an impact on different societal issues such as energy consumption and demand levels, food production, economic stress, natural capital impact, environmental degradation, labor force composition among others.



Figur 6 **Example of the integration of biophysical and economic variables using the DPSIR framework (Kristensen, 2004). Own elaboration.**

Fundamental aspects to understand the MuSIASEM approach

A) Integration of scales using Georgescu-Roegen's fund flow scheme:

This approach was developed integrating concepts from diverse fields such as non-equilibrium thermodynamics applied to ecological analysis (Odum, Ulanowicz), complex system theory (Kauffmann, Morowitz, Rosen and Zipf) and bio-economics into a semantically open narrative, that includes quantitative descriptions, in order to be able to describe the processes that takes part at different scales (Giampietro et al., 2009) considering them simultaneously into the sustainability analysis. The sustainability analysis is based on the viability and desirability of patterns of production and consumption of socio-economic systems and its feasibility based on biophysical elements.

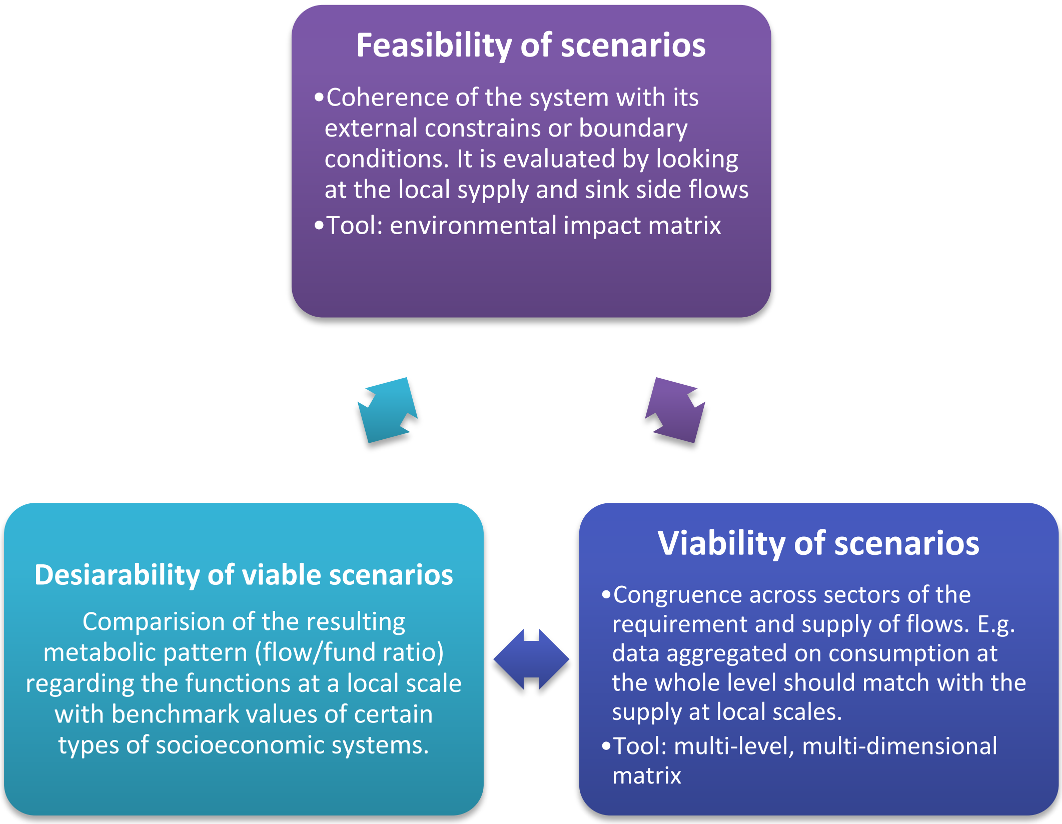
In order to keep track of all transformations implied in the societal development considering its biophysical roots, the categories developed in the Georgescu-Rogen model were adopted:

> ***Funds***: are the elements that remain the same regardless all transformations in the system during a period of time. Funds have the capacity of transforming input flows into output flows during the time scale of the representation and preserve themselves. They can be used only at a specified rate and are periodically renewed. Examples: land, population. Within MuSIASEM approach the fund responds *to what the system is made of*.
>
> ***Flows***: elements that disappear or appear over the duration of the representation, they can be an output without ever having being an input or vice versa. Flows in this case can be matter or energy controlled or dissipated. The size of these flows depends on internal (capacity of processing a flow, for instance, technology) or external (availability of an stock of

a natural resource) factors. Within MuSIASEM approach the flow responds to *what the system does.*

In MuSIASEM approach flows are characterized in relation to their funds, for instance, energy consumption per year per capita, water consumption per hectare because in this way it is possible to integrate with sufficient coherence different analysis dimensions required in the approach. With the use of funds and flows categories benchmarks as ratios of known typologies of metabolism are defined, for example, average work productivity per hour. As well, MuSIASEM idea of sustainability it is based on the maintenance and reproduction of the fund elements in the metabolic process of society during the period of analysis.

Regarding the sustainability assessment, MuSIASEM brings a method to make a sustainability check grounded on:



B) Sudoku Effect in production and consumption representation across scales:

MuSIASEM divides in societal levels for the analysis to analyze the consumption and production sides. The Sudoku effect implies that the characteristics of the parts must be compatible with those of the whole and vice versa nevertheless, there is no causal relation between them. By using a multipurpose grammar to perform impredicative loop analysis it is possible to construct a multidimensonal matrix that appeals to have a similar effect as the Sudoku game.

According to Giampietro et al (2009) the divisions of levels are the following:

- Individuals level (n-3)
- House holds and Paid work level (n-2)
- Economic sectors level (n-1)
- National level (n)

Is from this hierarchical division that the analysis of the requirement and production of material and energy flows in the society will be performed across levels.

Consumption side analysis

Individual level (N-4) consumption it is focused on the analysis of the fund Human Activity (HA) based on endosomatic metabolism, which means, the conversion of energy inside the human body into human activity. In order to make a profile of the population to analyze its total human activity there were set different structural types of individuals (a, b, c, d, e, f) in relation to their age and gender because each individual type has different activities within the society.

AGE	FEMALE	MALES
> 65 years	a	b
16-65 years	c	d
< 16 years	e	f

The human activity (HA) at the individual level is considered to be:

- Physiological overhead (HA_{PO})which includes non productive activities as sleeping, eating, personal care
- Paid work (HA_{PW}); includes economic activities performed by the individuak
- Household (HA_{HC+LE}): it includes chores (C), leisure (L) and education (E) activities, it can be considered the disposable not invested in PW.

The next graph shows the visual representation of the Human activity of a society in relation to its population composition and the activities performed. The numbers in the representation are calculated hypothetically considering a population of 100 individuals.

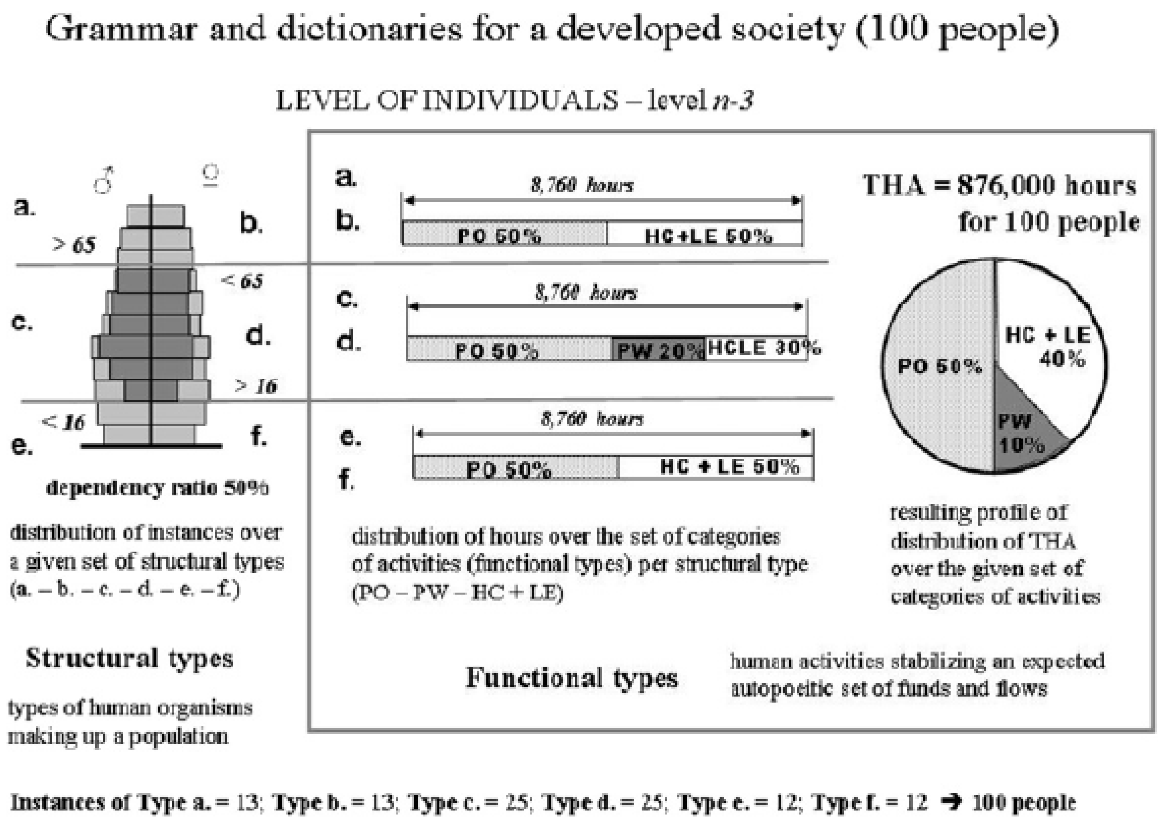


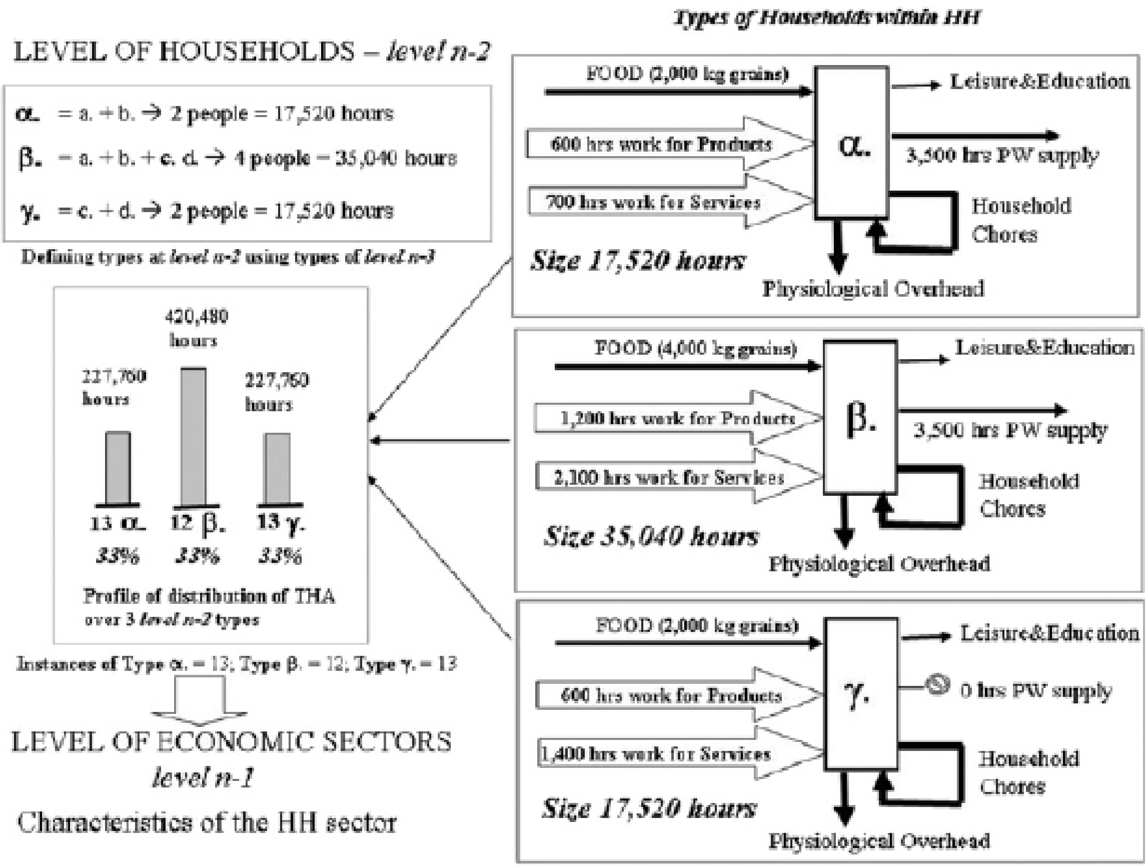
Fig. 1. Representation of endosomatic metabolism (level $n-3$).

Figur 7 **Individuals' characterization and human activity calculation for developed societies (Giampietro etGiampietro et al., 2009: p.5).**

House holds and Paid Work level (N-2) This level deals with the conversion of energy perceived as human activity within the socioeconomic process, for example, two adults and two elderly people will have the same amount of Human Activity but their share of this human time to the economic process will be greater in the case of the adults if we talk of a developed country context. There are 3 types of households defined using the categories of individuals of the previous level.

Type of household	Number of people	Age and gender
A	2	Couple of adults size
B	4	Couple of adults plus two children
Y	2	Couple of eldery

The structural composition of households will required from the production side services and products which at the same time requires energy, material and human time of work investments and supply hours of paid work to the rest of society. In the next figure we can observe a visualization where the different share of human time dedicated to the different activities of individuals varies within each household because its composition, we can observe the size of the household is measured by the total hours of human activity of that household and the requirements from the production side (products, services and food) of each household which will be further explained in the next level.



Figur 8 Human time required for consumption and human time allocation of paid work in different households profiles (Giampietro etGiampietro et al., 2009: p.6).

Economic sectors level (N-1)

Depending on the categories of Households and the population composition in each, the flow of products and services required can be calculated which at the same time is associated to an overall supply of paid work time. In this way a bridge between households and the rest of the economy by the assessment of the hours of human activity dedicated to the paid work. The paid work required should be compatible with the one that is supplied by households in the first representation. At this point, the characteristics and conditions of the socio-economic system will define technical processes used to generate the supply of paid work for example, the productivity of labor per hour or the biophysical productivity for products and services.

Linking Production with Consumption side through Metabolism indicators

In order to describe the production side of the society, it is needed to keep track of the allocation of the human activity in the different parts of the system. Two kinds of variables are needed to be distinguished: extensive variables (similar to funds in the Geourgescu Roegen model) which have the characteristic of being additives and intensive variables these variables can not be added and they represent a ratio during a period of time. For example, in order to calculate the exosomatic metabolic rate (which is one of the main indicators for the sustainability assessment using MuSIASEM) of certain compartment, for instance ”i”(ERMi), we would need to divide the exosomatic throughput of a given compartment (ETi) per hour of HAi, i.e., EMRi =ETi/HAi. In this way it is possible to set benchmarks of what is required in technical capital and exosomatic energy to boost the efficacy of 1h of human activity. The next illustration shows an example of this assessment in the production and consumption side of a society.

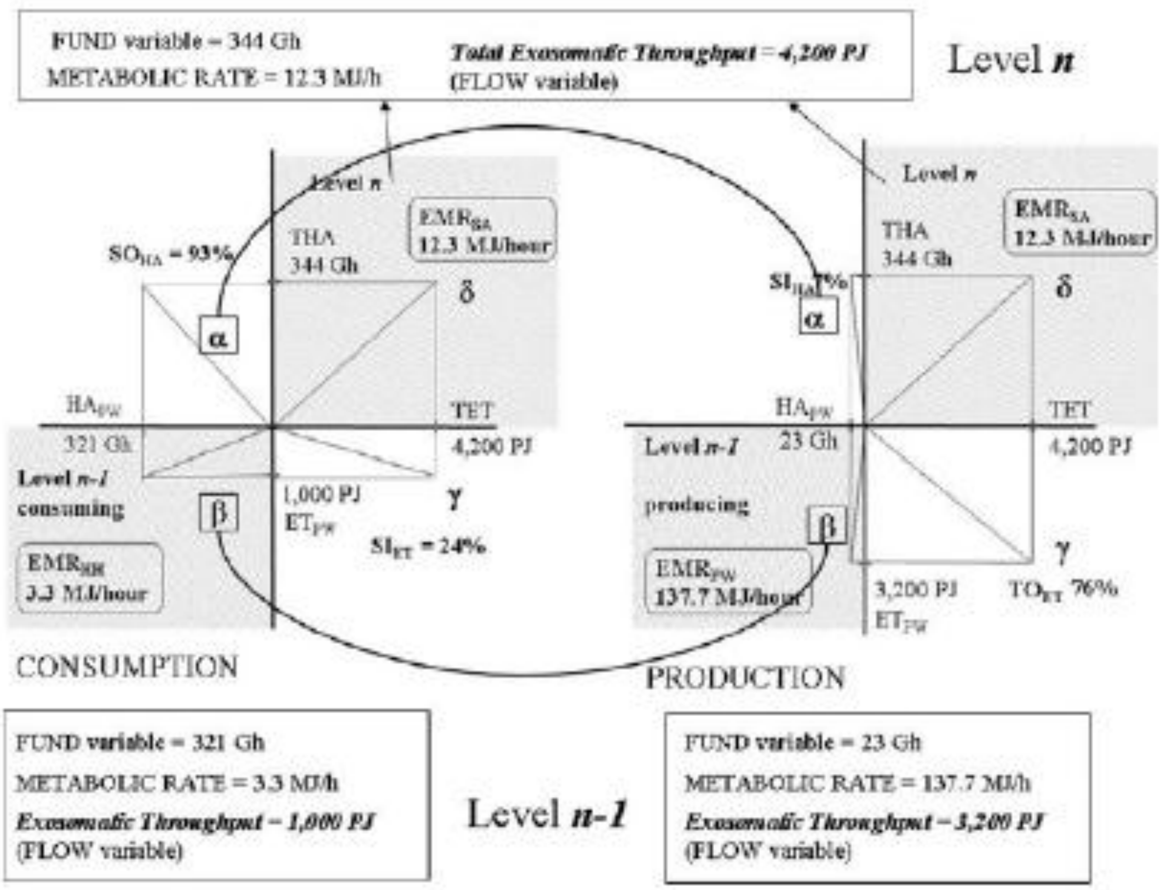


Fig. 4. Establishing a bridge between representations of exosomatic metabolism referring to consumption and production.

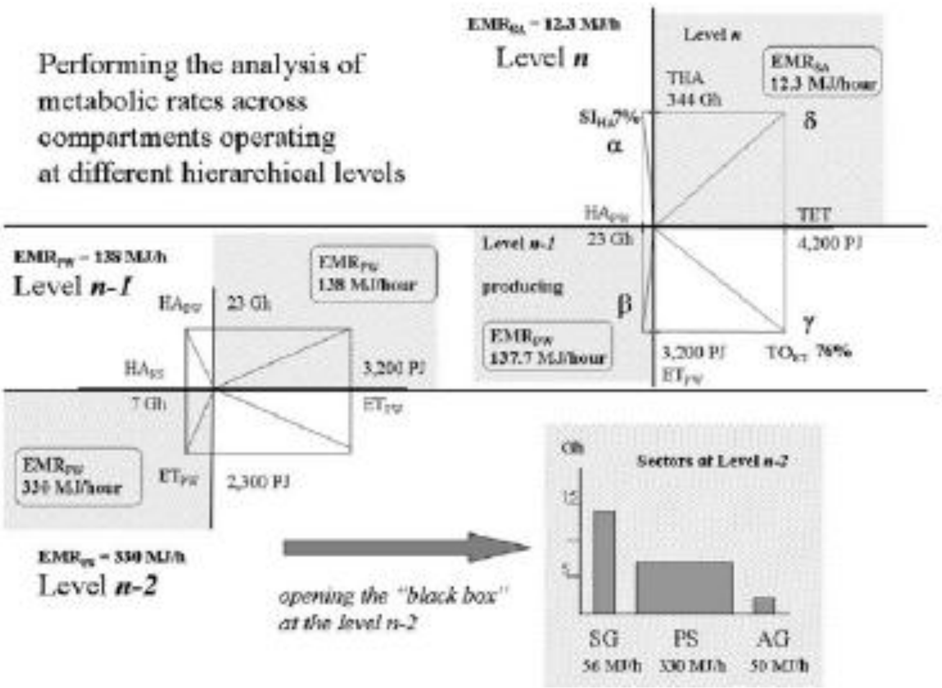
Figur 9 **Production and consumption comparison of metabolic rated of Spain 1999. (Giampietro et al., 2009: p.9).**

In order to make assessments of each levels using MuSIASEM the following variables are considered:

Variables	Level N	Level N-1	Level N-2
Extensive variables for fund HA	THA – total human time available for the whole economy (24h x 356days x population) $THA=HA_{PW}+HA_{HH}$	HA_{PW}: hours allocated in PW sector in a year HA_{HH}: rest of THA in HH sector in a year	HA_{PS}: total labor hours in Paid sector for 1 year. * Units Gh PW sector in this level is divided in PS (industry), SG (services and government) and AG (agricultural sector)
Extensive variables for flow ET	TET – total exosomatic energy consumption in joules for the whole economy in a year. $TET= ET_{PW}+ET_{HH}$	ET_{PW} - exosomatic energy consumption for the PW sector in a year ET_{HH} - exosomatic energy consumption for the HH sector in a year.	ETPS: exosomatic energy consumption in paid sector in a year. * units: PJ
Intensive variables	EMR_{SA} - how much exosomatic energy is consumed per hour of human time in the whole society. $EMR_{SA} = TET/THA$	$EMPR_{PW}$ - how much exosomatic energy is used per hour of labor in the PW sector as a whole. $EMPR_{PW} = ET_{PW}/HA_{PW}$ Fund share N-1/N: indicates how much human labor is used in the PW sector compared to THA. This value is determined by conditions as the demographic structure, social rules, habits, education level and workload of workers. Measured as ratio of HA_{PW} / THA Flow share N-1/N: how much energy is used by the PW sector compared to the total energy consumption of the whole economy. Calculated as ratio of ET_{PW}/ TET	EMR_{Ps}: how much exosomatic energy is used per hour of labor in PS (production sector - industry) as a whole. $EMR_{Ps}= ET_{PS}/HA_{PS}$ * units: Mj/h Fund share N-2/N-1: fraction of labor used in PS (industry) compared to HA_{PW} in the PW sector. Ratio between HA_{PS} (N-2) and HA_{PW} (N-1) * Units % Flow share N-2/N-1: fraction of exosomatic energy used in PS in relation to the exosomatic energy in PW as a whole. Ratio between ET_{PS} (N-2) and ET_{PW} (N-1)* Units %
Indicators congruence production	Bio-economic pressure: indicates the degree of pressure generated by the expected life style and the structure of the consumption sector over the technical performance of the production sector (industry). TET/HA_{PS} consumption		

and consumption	Exosomatic hypercycle[5]: ability of production sector (industry) to generate a biophysical surplus of products using only a small fraction of TET and THA for its operation. TET/ $HA_{PS\ production}$

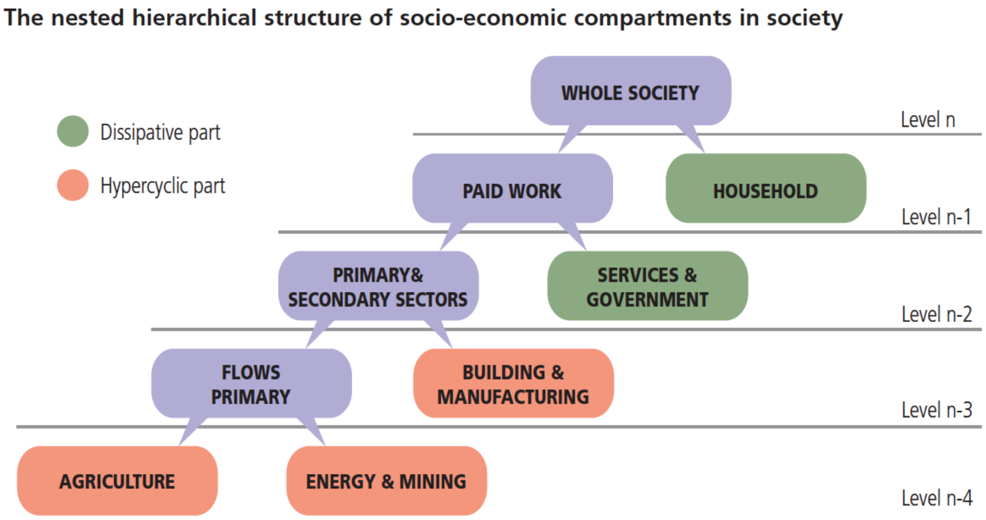
The next illustration is an example of a metabolic analysis across levels.



Figur 10 Analysis of metabolic rated across levels. Spain 1999. (Giampietro et al., 2009: p.12).

[5] In Eigen's ecological theory, hypercycle is one of the two parts in which a network of mater of energy flows can be divided; the other is the dissipative part. Hypercycle is the part producing a net supply of energy for the rest of the ecosystem. In MuSIASEM it refers to the ability of delivering an amount of products and useful energy to the rest of the economy. The higher the strength of the hypercycle, the larger is the fraction of Human activity that can be invested in services, education, leisure and social interaction. (Giampietro et al. 2013) In SD terms, this hypecycle can be considered as the existence of a positive feedback loop which with other variables increase the efficiency to deliver more products for the society using less human activity and total exosomatic throughput like a reinvestment.

The next figure shows an extended division in which MuSIASEM manages the societal data. The green sectors are Division levels of society characterized by its dissipative part (consumption of material and energy flows for end uses) and its hypercycle part (reinvestment of material and energy flows for the reproduction of those flows).

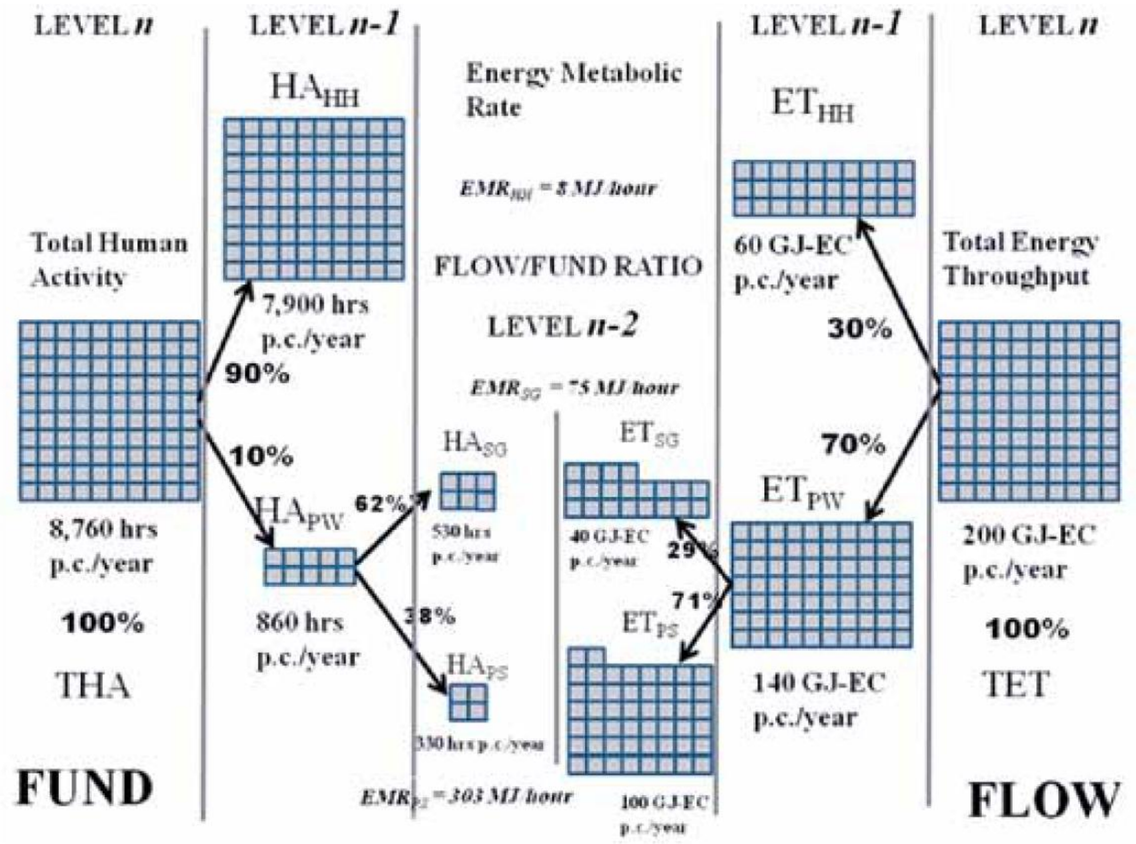


Figur 11 Societal level, extracted from Food and Agriculture Organization from Unitated Nations working paper ”Application of the MuSIASEM approach to three case studies”, October 2013

Tools for the analysis

Multi-level / Multi-scale accounting: it is related to the ”holon” theory by Koestler where each part of the system conforms a larger part and this part subsequently conforms the larger whole. Each part is possible to be analyzed by looking at its lower or higher level by the identification of its structural and functional relations.

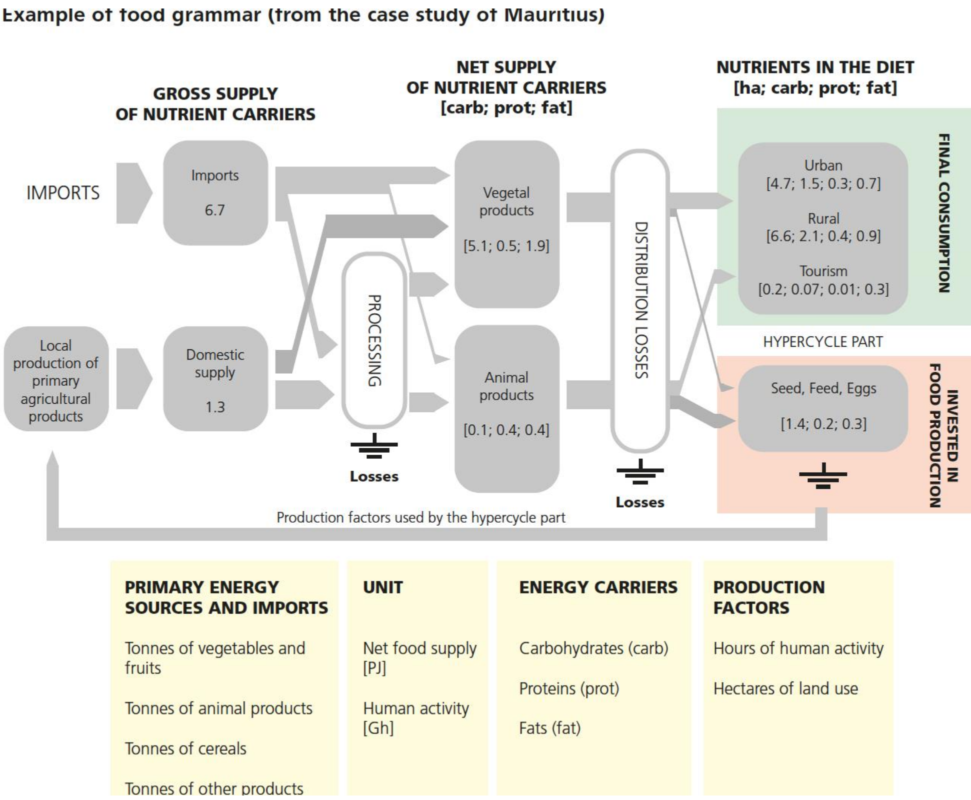
Dendrogram representing the profile of investment of the fund element human activity and the flow element energy



Figur 12 **Dendrogram on Energy and Human Activity, eExtracted from Food and Agriculture Organization from Unitated Nations working paper "Application of the MuSIASEM approach to three case studies", October 2013.**

Multi-purpose grammar: provides a description at an explanatory level of the relations between semantic categories. It is semantically open because it defines the system fundamental characteristics depending the desired focus of analysis.

The next figure shows an example of a multipurpose grammar. These kinds of representations are developed in MuSIASEM application on water, energy and food issues.



Figur 13 Food grammar, extracted from Food and Agriculture Organization from Unitated Nations working paper ”Application of the MuSIASEM approach to three case studies”, October 2013

Impredicative loop analysis: comes from ecology. It implies that the characteristics of the parts must be compatible with those of the whole and visceversa. Nevertheless, there is a circular causal relation between them. By using a multipurpose grammar to perform impredicative loop analysis it is possible to construct a multidimensonal matrix that appeals to have a similar effect as the Sudoku game. With these matrixes it is possible to identify congruence constrains across level and dimensions.

Multi-level matrix characterizing the metabolic pattern of Mauritius

		Flow elements			Fund elements			Money (billion USD)
		Food (PJ)	Energy (PJ-GER)	Water (hm³ extraction)	HA (Mhr)	PC (GW)	Land (Kha)	
Consumption	HH	5.9	16	98	10,000	1.5	28	n/a
	PW*	0.8	37	11	600	1.1		8,200
	AG	1.3	negligible	100	39	negligible	21	210
	EM	n/a	2.2	260	8	0.03	negligible	180
	exp_{pw*}	n/a	n/a	3	590	n/a	n/a	50% GDP
	exp_{ag}	negligible	0.36	1,100	39	0.02	51	2.5% GDP
	Whole	8	56	1,700	11,300	6.0	100	9,800 (GDP)
Supply	Imports	6.7	19	n/a	n/a	n/a	n/a	63% (GDP)
	Domestic supply	1.3	7	1,700	11,300	6.0	100	9,800

Figur 14 . Multi-level matrix, eExtracted from Food and Agriculture Organization from Unitated Nations working paper ”Application of the MuSIASEM approach to three case studies”, October 2013

Core concepts definitions

According to MUSIASEM literature[6]:

Societal Metabolism*:* *notion used to characterize the processes of energy and material transformation in a society that are necessary for its continued existence, sustainability or Autopoiesis. In order to maintain this, those transformations cannot overpass the thresholds posed by the Ecosystem Metabolism. Both, societies and ecosystems are levels of a Hierarchical System. In them, there are relations that have to be maintained within and among the levels, including the relations that control the biophysical transformations, or metabolic patterns. The metabolic patterns of the social level of a hierarchy depend on its internal and external relations. They pose internal and external constraints to the autopoesis of the system.*

Primary Energy Sources (PES) *and Imports: refers to the energy forms found in their original biophysical form (e.g. coal, gas and oil reserves, blowing wind, falling water, sun radiation, and biomass) that should be expressed in biophysical quantities such as tons of Coal, tons of falling water for hydro, kg of uranium, etc.) that generate the supply of energy carriers used by societies. The original role of PES is to indicate the requirement of favourable gradients which must be available, in order to be able to produce an adequate supply of energy carriers (entering into the system from the left of the figure). This determinant indicates the supply side limitations.*

Gross Energy Requirements (GER): *the gross requirement of energy carriers are determined by the potential domestic supply of energy carrier generation either from the PES sources or from Imports, usually expressed in Giga Joules (GJ-GER). The formalization of GER results from a convention over the energy potential of each source that depends on (1) the type of conversion process they are entering into, and (2) the type of energy carrier they are used to produce (either mechanical energy or thermal energy). It corresponds to the total energy throughput taken from the natural processes either locally or through imports. It is obtained after the conversion losses (energy carriers used to make other type of energy carriers – e.g. electricity generation) have been characterized (the internal loop labelled "Hypercycle Part" in the figure)*

Net Energy Requirements (NER*)* *: the net energy requirements are defined by the sum of the final consumption of energy carriers (either thermal or mechanical, expressed in GJ-EC) made available to the various final compartments. It makes possible to compare the net surplus of energy carriers delivered to the society with the internal consumption within the Energy and Mining sector generating the energy carriers (hypercycle part). The net energy requirements entering into the dissipative part account for the two types of losses: (i) losses of conversion; and (ii) losses of distribution. In formal terms, the net supply of energy carriers (NSEC) equals the overall net energy requirements (NER) for thermal energy and mechanical energy respectively.*

Human activity (HA): is one of the key factors in the analysis of the metabolism. It refers to the human time measured in hours obtained considering the total of the population times the hours existing in one year. This time is allocated in paid work activities or households activities depending on the demographic composition and socioeconomic characteristics of society.

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[6] Giampietro, M. Integrated Societal Metabolism research line of the IASTE group. Electronic source: http://societalmetabolism.org/?page_id=412

Chapter 4

Argentina Case: energy analysis from 1990 – 2007

Argentina Case: energy analysis from 1990 – 2007

The case selected for the MuSIASEM testing was on the Argentina's energy intensity development from 1990 to 2007 extracted from the article "Going beyond energy intensity to understand the energy metabolism of nations: The case of Argentina" by Marina Recalde from Instituto de Investigaciones Economicas y Sociales del Sur (IIESS) de la Universidad Nacional del Sur (UNS) and Jesus Ramos Martin from Universidad Autonoma de Barcelona (UAB). Information on the case described in the next sections is from the analysis of the studied article's authors , i.e., the analysis performed previously and after the modeling activity corresponds to replicability efforts only of the information in the article .

Context of the energy system in Argentina

> *"… Energy supply problems appeared from mid 2004. Energy supply restrictions were common during the period 2004-2007 and reduced during 2008 and 2009, when the rate of growth of GDP was lower. However, during winter 2010, industries faced power shutdowns both as a result of a very cold winter and the return to the economic growth path, which tightened supply. … Industrial activity displayed an inter annual decrease of 2.3% in July 2010 as a result of the shortages in natural gas (NG) supply and the requirements of more expensive substitute fuels. This reflects one of the main characteristics of Argentina, its high dependence on hydrocarbons which accounted for 86 % of Total Primary Energy Supply (TPES) in 2009,2 with NG accounting for 52%, while New Renewable Energy Sources (NRES) have not yet succeeded in the Argentinean energy market; despite it is a naturally well-endowed country."*
>
> *(Recalde &Ramos, 2011)*

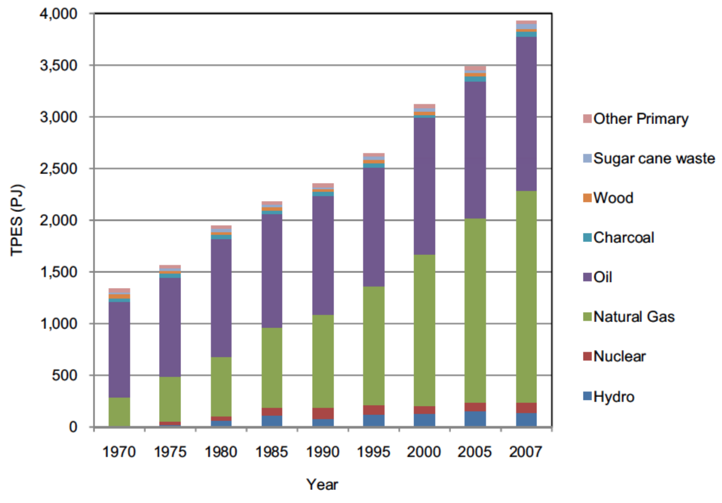


Fig. 4. Evolution of TPES in Argentina 1970–2007. Source: Own elaboration based on Secretaría de la Energía de la Nación.

Figur 15 **Argentina Energy primary energy sources from Recalde & Ramos (2011)**

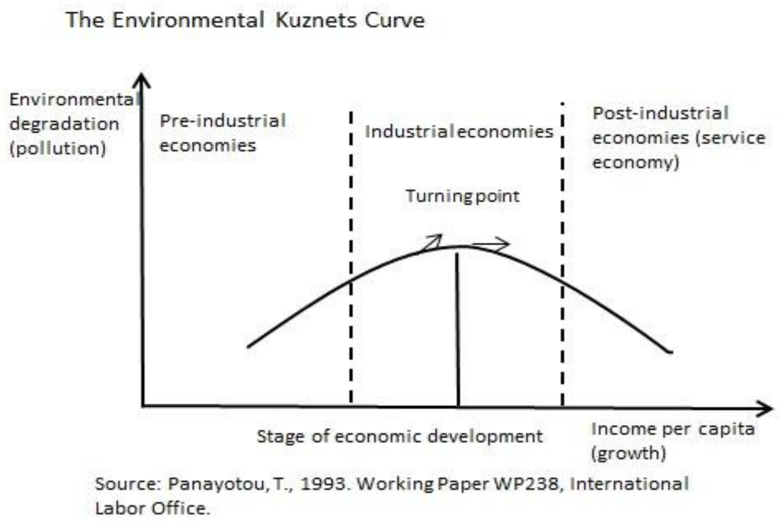
The recount on the energy management in Argentina during the past 5 decades presented a bad performance of the energy resources and past energy policies characterized by liberalization and deregulation that leaded to an over exploitation of nonrenewal energy resources and abandonment of the energy policy and planning. Lately there is been an increasing concern on the Argentinean energy, economic and environmental future, and the growing opinion that a change in the energy model is needed.

Theoretical background

Responds to the dematerialization, that imply there is a reduction in material and energy consumption along the economic growth path, which is very closed to energy intensity implications because it is believed that a society will have to come to a degree of post industrial economies in order to have reduce the burden on environment. The level of consumption of energy and materials are explained by income.

There are three main arguments supporting the energy intensity concept and the EKC:

1) Scale effects: increase in energy and materials consumption (and environmental degradation) as a result of more economic activity
2) Composition effects: decrease in material and energy consumption and it refers to the change in the share of each economic activity out of the total activity
3) Technology effects: decrease in material and energy consumption it relates to higher levels of income to higher technology development, and this to lower energy use per unit of output.
4) Changes in consumption patterns: environmental quality demand when development increases



Figur 16 **Shaw William, Will Emerging Economies Repeat the Environmental Mistakes of their Rich Cousins?, March 1st, 2012, Carnegie endowment for international peace.**

Analyses performed on Argentina's Case

There were two kind of analysis performed and their focus of study:

- ✓ **Conventional Analysis:** relation between energy consumption and GDP (Gross domestic product). Widely used to measure, in broad terms, energy efficiency in end use devices to capture structural changes in the economy. It does not consider causality or non-linear effects on the energy process.
- ✓ **Non-conventional, MuSIASEM Analysis**: Complement the conventional perspective on the intensity of use of energy and provide insights on the Socio-economic development and Environmental pressure of energy consumption debates. Innovation: combine intensive and extensive variables with information from different fields (demographics, biophysical and monetary) in order to explain the evolution of society, its development constrains and the allocation of scarce resources including human time. Differentiate the material or energy use of productive or not productive sectors of the system.

Conventional analysis performed
Evolution of the energy intensity in Latino America 1970-2008

There are two parts that creates the energy intensity: 1) The Total energy consumption unit and 2) the GDP unit, both changes because of specific reasons. Energy intensity does not always reflect the behavior of the final energy consumption. The total primary energy supply considers losses until it becomes final energy.

In Argentina due the economic policies implemented and the financial instability the energy intensity fluctuates while the final energy consumption kept a positive growth rate.

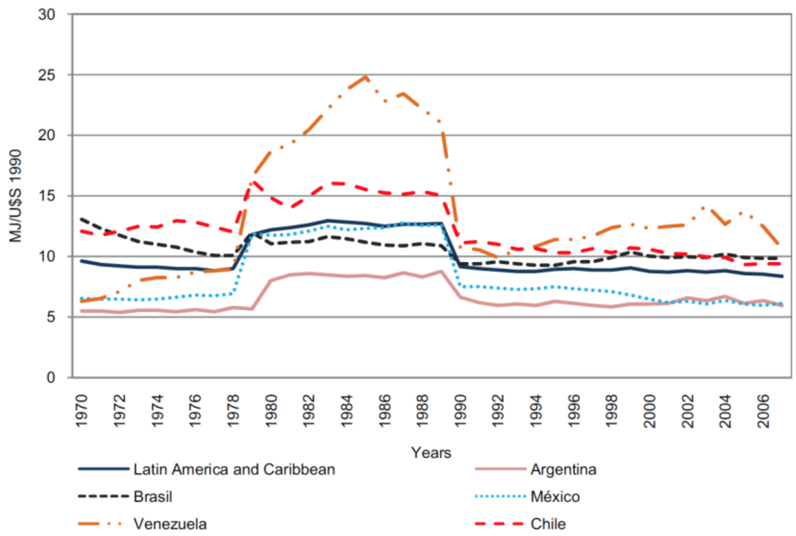


Fig. 1. Energy intensity of final energy consumption of Latin America and Caribbean region and countries. 1970–2007. Source: Own elaboration based on OLADE/SIEE (Latin American Energy Organization /Energy Environmental Information System).

Figur **17 Energy intensity in America Latina extracted from Recalde & Ramos (2011).**

Non conventional analysis - Societal metabolism
Notion used to characterize the processes of energy and material transformations in a society that are needed for it to continue its existence. MuSIASEM provides the framework and units for each scale of analysis or level. In this application case there were 3 levels considered: Level N or national, N-1 or production and consumption activities and N-2 that corresponds to the disaggregation of Paid work, Agriculture, Services and Government

Conclusions from the article
1) The consequence of being more inefficient progressively regarding the energy use will obligate Argentina to allocate more working hours to production making changes in population related issues such as reducing the time for leisure or dependent population.

2) The main reasons of the non-desirable path of energy intensity are a) the productive structure of the economy, b) the energy consumption composition by sector and c) the particular share of fossil fuels in the energy mix.

3) Argentina as energy supplier country presents as high metabolic rates in the different productive sectors, nevertheless, even though economic development exists some degree of Dutch disease is harming local industry.

4) The SG sector has high energy consumption level which is translated in a less diversified economy.

5) Productivity of labor has increased which implies an enhanced level of capitalization. The industry (PS) got worse during the period of analysis, meaning that the labor productivity ($US/ hour) occurs by reducing efficiency of use of energy. Argentina was a net exporter of energy. Rising in prices are expected to achieve an increase in labor productivity unless there are major changes in the economy.

6) Energy consumption patterns of Argentina is worrying, its reserves are only 2.59 Gbbl[7] of oil and 446.16 Gm3 of natural gas. If, in the close future, Argentina become a net energy importer will keep an economic structure heavily dependent on exosomatic energy.

Importance of the framework according to the authors

There are two main reasons identified to perform the MuSIASEM analysis

1) Complementary analysis for the economic assessment. It makes it possible to study different dimensions of the reality such as economic productivity and competitiveness, quality of life and equality, and environmental impact of natural resources consumption, all of them at different hierarchical levels.
    a. A comparison of different economic systems and their historical development is possible with the use of MUSIASEM framework trough the relationship between human activity, energy use and economic production as well as the study of the evolution of the productivity of labor and the productivity of energy of a particular sector.

2) Avoid misleading analysis: evolution of energy intensity may hide the fact that, on a longer time-window, energy efficiency did not increase, but instead shows that increases in energy consumption did not imply efficiency increases.

Analysis on the application of MuSIASEM using SD methodology

In order to build a SD model with the information on the application case of MuSIASEM methodology, the variables used to assess the energy use in Argentina, results, main findings and information in the article were analyzed. The next sections shows the information gathered.

Variables identification

MuSIASEM results an application of Georgescou's fund-flow model deriving its variables categorization on it, nevertheless, variables in the article were categorized in the following way:

Extensive variables

- ✓ ETPW: Exosomatic Throughput paid work: Total primary energy used in the paid-work sector in one year.
- ✓ ETHH: Exosomatic Throughput households: Total primary energy used in the household sector in one year.
- ✓ TET = ETPW + ETHH
- ✓ GDP: Gross domestic product
- ✓ THA: Total human activity
- ✓ HA PW: Human activity paid work
- ✓ HA HH: Human activity households

As intensive variables or indicators:

[7] Commonly used to express billions of barrels, it results an adaptation from computer language "gigabillionbarrels"

- ✓ EMRSA= TET/THA: Average Exosomatic Metabolic Rate: Energy consumption per hour of human time available to the society.
- ✓ EMRPW = ETPW/HAPW: Paid Work Exosomatic Metabolic Rate: Energy consumption in the paid-work sector per working hour available.
- ✓ EMRHH= ETHH/HAHH: Household Exosomatic Metabolic Rate: Energy consumption in the household sector per household hour available.
- ✓ ELPi = GDPi/HAi: Economic Labor Productivity: Added value per hour of working time in sector i.
- ✓ ELPi/EMR = GDPi/ETi: Energy Efficiency of Production: Added value generated per unit of energy consumption in sector i, measured in U.S. dollars/Joul

The metabolic rate, as we are going to see in detailed in the next table, is an indicator that measures the energy consultation per the household or paid work time.

At this point, the article does not distinguish between funds and flows variables in the analysis which might be useful for the model conceptualization.

Results identification[8]

The information on the reported results were categorized by: a) identified facts under the period of analysis, b) causality explained in the article narrative, not part of MuSIASEM literature and c) existence of any MuSIASEM indicator regarding the results.

N Level: Argentina

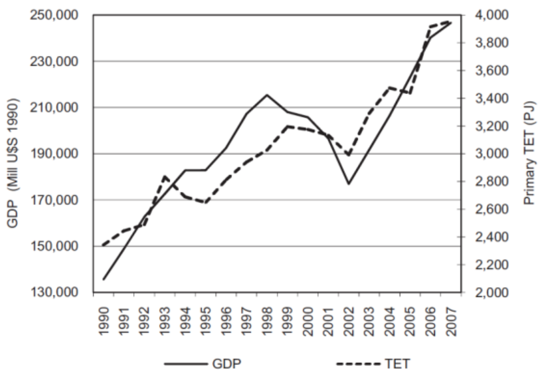
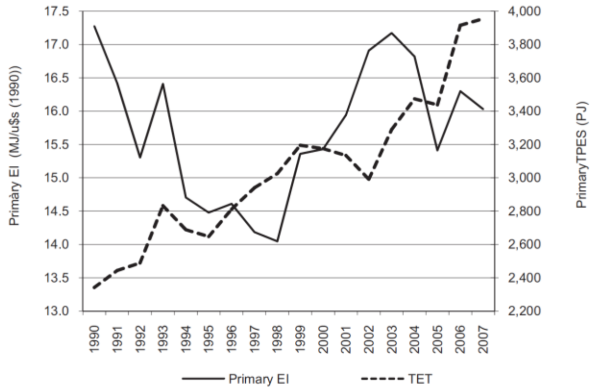
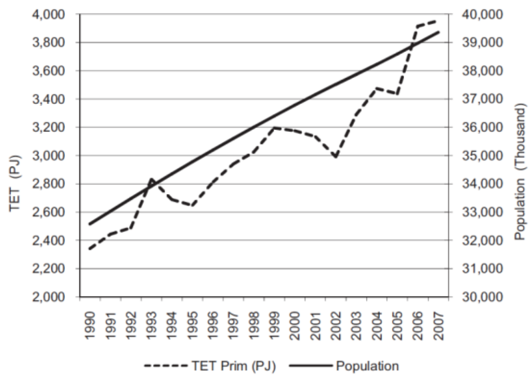
<table>
<tr><th>Identified Facts during the period of analysis</th><th>Causality</th><th>MUSIASEM Indicators</th></tr>
<tr><td>GDP and energy consumption has a similar evolution and similar cycles.</td><td>Not explained in the article,.</td><td>GDP and TET</td></tr>
<tr><td>GDP and energy consumption doubled their values</td><td>Not explained in the article</td><td>GDP and TET</td></tr>
<tr><td>TET was higher than for GDP, except
in 1996-1997, 2003-2004 and 2007, with the consequent


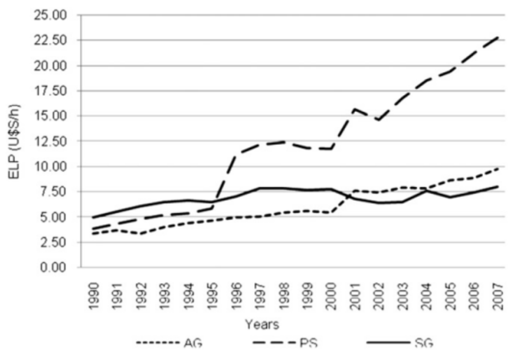
Fig. 5. TET and GDP evolution. 1990–2007.

impact over energy intensity and EMRSA</td><td>The increase in the level of energy consumption per hour of activity was directed to both increasing the level of capitalization at work and at home</td><td>EMRSA exhibits a positive trend which oscillates between 8.2 and 11.47 MJ/h</td></tr>
</table>

[8] All graphs analyzed from results are extracted from the article “Going beyond energy intensity to understand the energy metabolism of nations: The case of Argentina” by Recalde and Ramos (2011).

Energy intensity has grown  **Fig. 3.** Evolution of energy intensity and total primary energy supply in Argentina. 1990–2007.	Argentina financial crisis (GDP reduction) even while energy consumption decrease	No particular indicator or Graph
Energy intensity presents an N shape with 3 turning points: 1999, 2003, General period 130 *M. Recalde, J. Ramos-Martin*  **Fig. 6.** Population and TET evolution. 1990–2007.	1) 1999-2002 GDP decreased more than energy consumption (energy indivisibility: of capital on energy prices) 2) 2003: Energy Consumption increased more than GDP 3) General: population growth was constant and was followed by the energy consumption (energy consumption had been devoted, partially, to cover population growth with a minimum of energy consumption).	No particular indicator or Graph

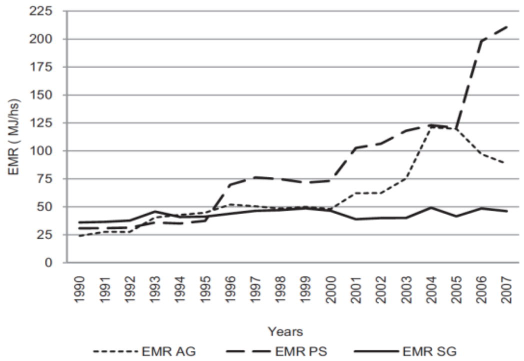
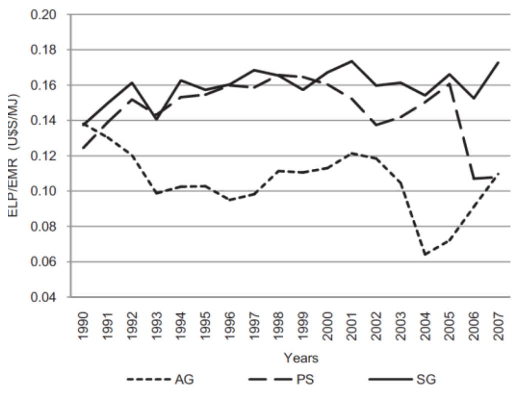
N-1 Level: Production and Consumption in Argentina

Facts during the period of analysis	Causality	Indicators
Total Energy Consumption smooth positive trend  **Fig. 9.** ELP_{AG}, ELP_{PS}, and ELP_{SG} evolution. 1990–2007.	Production side (PW) and consumption side (HH) that have increased steadily, almost doubling. Population growth directed to the non-working fraction Working population decreased almost 50%. Article explain due to emigration for economic reasons Detail: increasing ETPW and reduction of HAPW resulted in an increase in	EMRSA increased in 39% EMRHH increased in 44% EMRPW increased 128% EMRPW has grown much faster than EMRHH ELPPW grew but less than EMRPW: 1991-1992, 1996-1997 and 2003-2004

	the level of capitalization at work, nevertheless the increase in capitalization of workers could not be exploited because of the loss of skills implied by the decrease in working population.	

N-2 Level: Evolution of the productive sectors:

Agriculture,(AG), industry, energy and mining (PS) and services and government (SG).

Facts during the period of analysis	Causality	Indicators
Working time in services and government increased, decreased 50% in the primary sector (agriculture) decreased more than 66% in the secondary sector (industry)  **Fig. 8.** EMR_{AG}, EMR_{PS}, and EMR_{SG} evolution. 1990–2007.	Article explains that this is reflecting not only a mechanization process in agriculture, but may also indicate a structural change toward a service economy, as well as an industrial decline.	Not available.
ETAG and ETPS doubled in the period ETSG only increased 50%  **Fig. 10.** ELP/EMR_{AG}, ELP/EMR_{PS}, and ELP/EMR_{SG} evolution. 1990–2007.	The capitalization of the services sector increased a bit, reflecting the fact that energy consumption in the sector increased faster than working population	EMRAG (growing 300% in the period) and EMRPS (growing 600% in the period) ELP doubled in the case of services (despite the increase in working population), it grew 200% in agriculture and 450% in the secondary sector (because of the drainage of working population)
Fossil-fuel reserves of Argentina are decreasing rapidly	Despite the dramatic increases in energy consumption, and in energy per hour of work, this did not translate in a better use of energy over the period.	Energy efficiency (ratio between ELP and EMR)

Model building process

The first attempt to apply the MuSIASEM framework into a SD model was obtained with the information in the article "Going beyond energy intensity to understand the energy metabolism of nations: The case of Argentina".

Equations provided in the article:

1. To calculate level N primary energy consumption, excluding non-energy use:

$$PEC = TFCPS * ESOUPS * L$$

where PEC: primary energy consumption; TFPPS: total final consumption primary sources; ESOUPS: energy sector own use; L: lose.

Added clarifications:

1.1. For level N-1 we use Total Final Consumption plus the energy sector, non-energy use.

1.2 For level N-2: energy sector consumption and transformation loses to each of the final consumption sectors according to their share in final energy consumption.

2. To calculate $HAi = W* POi * HsSi$

where HAi: total human activity for the activity i; W: working weeks per year; POi: population in the activity i; HsSi: weekly hours of work in the activity i.

Out of the variables and equations from the article and the authors's narrative a structure lacking stocks and flows were obtained. Although the framework in its principles states the categorization of variables in funds and flows in this application case, there is no distinction between them. Based on the SD methodology, the dynamic behavior comes from the interaction between stocks and flows over a period of time within a certain system boundary.

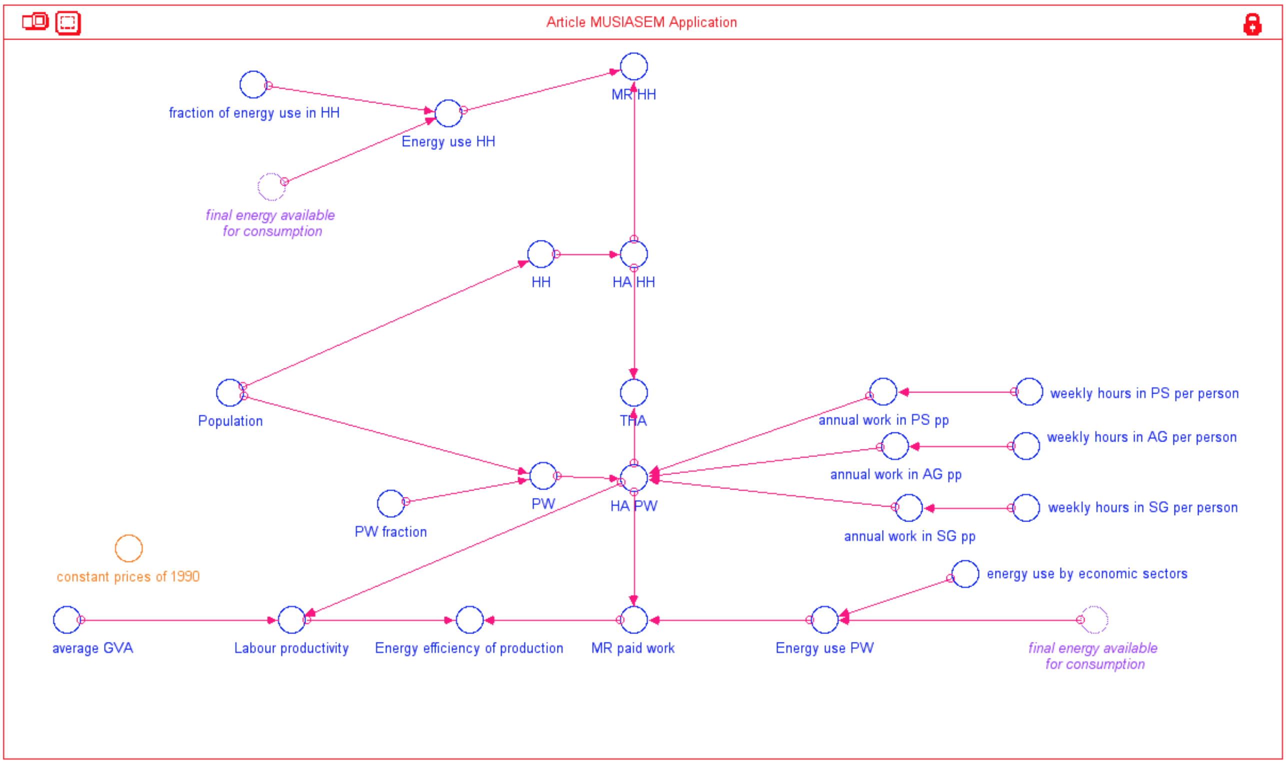
The equations from the SD model structure are placed in the appendix section.

Human activity structure

Human activity is a variable obtained from the total number of people and the time in a year measured in hours. This human time it is allocated into *Human Activity House Holds* (HA HH) and the time invested in productive activities or paid work (HH PW), the amount of human activity in each comes from the calculation of the working weeks per year and the weekly hours of work in each economic sector. In the article it is mentioned that the HH PW reduces the Leisure time that is part of the HA HH components, nevertheless, it is not explained how this balance might happen. Also it does not say how exactly *human activity* in households is calculated.

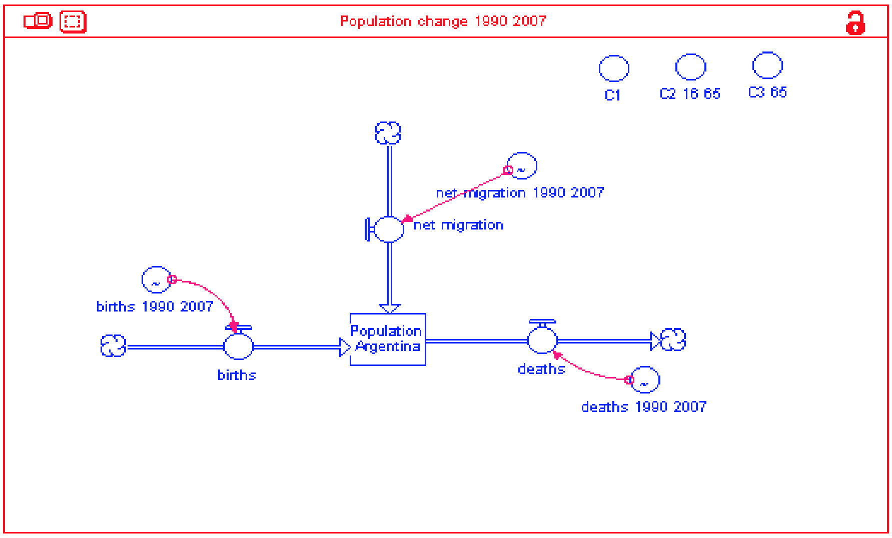
Energy consumption is an important variable into the analysis and it shows an inconsistency in its understanding. According to the article, it is calculated trough the income, population, and losses rate while MuSIASEM approach shows at the same time a different way of assessment of the energy consumption within the different societal levels that will be explained in the next page. The units used for the *human activity* assessment resulted to be consistent and coherent. The Gross Value Added (GVA) per sector during each year was obtained from National Statistics according to the authors but this value might represent an average of the diversity of activities performed in each sector but the information on how that value was accounted by the initial source is unknown for us. In order to calculate the economic labor productivity per sector, these values per year are needed. The variables in orange are expected to be included in the modeling effort because they were implicitly mentioned in the article; nevertheless it did not show a specific way of incorporating them that is why they were left in a side.

The structure regarding the Human Activity in Argentina is the following:



Figur 18 SFD Human activity structure on Argentina Case

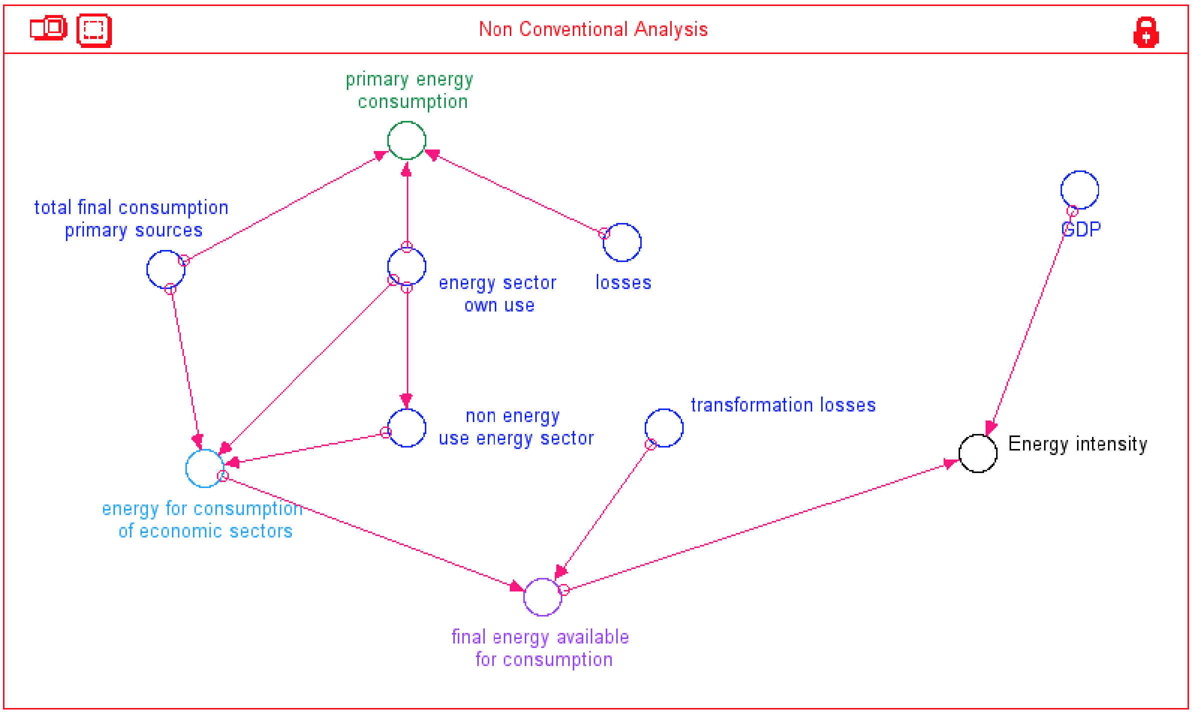
We can see how population comes to be important into the analysis because it is from the number of people that the *human activity* that supports the economy's labor requirement comes from. According to MuSIASEM indicators such as labor productivity, energy efficiency or production the metabolism of a specific sector is related to the *Human Activity* in each sector. In the article it is explained how the economic crisis provoked an increase in the emigration rate, affecting the labor available for specific sectors. One example on how SD methodology will aid to the explanatory capacity of MuSIASEM would be the appropriate incorporation of stocks and flows to the issues analyzed, for instance, the next structure could improve the understanding of changes on the ”metabolism indicators” based on changes on population over the period of analysis.



Figur 19 **SFD of Population structure on Argentina's Case**

Energy analysis structure

The next structure shows a how a conventional analysis on what energy intensity, variable in black, is usually done, a ratio of final energy consumption and GDP. Several critiques have been attributed to this kind of analysis because the misleading understandings it might bring, i.e., one may interpret improvements on energy intensity levels because the indicator shows it to decrease therefore we think the system is requiring less energy inputs or it is using more efficiently its energy supply when in reality GDP is raising without necessarily implications on the efficiency of energy use or the decrease on the general amount of energy consumption, or even cases when GDP is decreasing and energy intensity is increasing due this reduction and not because of an actual increase on the final energy use. Energy intensity comes to be just an indicator without explanatory capacity on how the two variables which create it change over time.



Figur 20 SFD of the Energy assessment on Argentina Case.

The rest of the structure is part of MuSIASEM application. In this sense, we can observe how *energy intensity* is an indicator based on the final consumption of energy, without considering the extraction, production and distribution loses or the availability of primary energy sources. MuSIASEM divides society in different levels and propose an energy accounting way to measure how much energy is required by society from the availability, production and end uses of energy. In this case, the primary energy consumption corresponds to the overall consumption of energy, required to measure the metabolism of the whole society "level N" (total energy use/ total human activity). The blue variable refers to overall amount of energy consumed by the economic sectors of society and households. In this case, the information in the article is unclear in the way this was calculated. It seems to be considered by the article as the energy required by economic sectors for fulfilling its functions, for production of more energy and the one that is allocated in households. The variables in purple refer to the final energy available for consumption that included the transformation losses. This energy is the one that is allocated in specific economic sectors.

The article presents total numbers of types of primary energy sources of MWatts. Nevertheless, the total energy consumed by sectors is provided in joules units. Along the article narrative it is not explained how this transformation takes place, making impossible to judge the right units use in the analysis.

Considerations of SD analysis to understand MuSIASEM application

The purpose of the application of MuSIASEM framework to the analysis was to understand the societal metabolism of Argentina towards a sustainability assessment. Nevertheless, with the information provided, the explanatory capacity of the article is limited. The model cannot address all conclusions drawn by the authors because they refer to structures of the socioeconomic system missing from the analysis.

While using the SD methodology to analyze the case we found it is hard to know how the energy required by economic sectors is weighed because it is result of other absent variables and dynamics characterizing the economic identity of Argentina, for instance these variables could refer to: biophysical productivity of services, biophysical productivity of products, and labor productivity in agriculture.

Although the explanation of what happened in Argentina 1990-2007 according to the article is helpful to hypothesize the development of the energy intensity slope and to contextualize the metabolisms indicators, the model building process presents prior problems which is the categorization of variables, the clarity on the equations, the structure lacking of declared feedbacks, specific delay times and appropriate causality of how variables are changing. The structure built with the information from the article is insufficient for an appropriate analysis using SD methodology.

It is hard to say if the application of MuSIASEM corresponds to an interpretation of the article authors or to the actual content on how to use the framework. Therefore, in order to clarify variables and knowledge gaps, a deep look into the MuSIASEM published literature was done. Considering the variables in the article as a starting point to understand the "societal metabolism" which is the main concept of MuSIASEM the Causal Loop Diagram (CLD) in the following page was built.

The main elements of the societal metabolism analysis in MuSIASEM framework are the accounting of the Human Activity element and the Energy production and consumption in a society across scales. There are apparently 3 feedback loops elicited from the literature:

- B1) Negative feedback loop that regulates the human activity allocated in households and paid work. *human activity* in paid work decreases the human activity in households, meanwhile, human activity in households can provide more human time to be allocated in Paid work
- B2) Negative feedback loop active when economic sectors are demanding more human labor than the standard amount of labor needed; there is a gap that will decrease the households' time, which can decrease the time dedicated to education, leisure or physiological overhead activities.
- R1) Positive feedback loop in the energy transformation process, it is called "hypercycle" in the literature, it refers to the energy out of the production that has to be reinvested again in energy production to maintain the reproduction of energy for consumption through the time

There are 3 level of society considered in the application of MuSIASEM framework to the Argentinas Case:

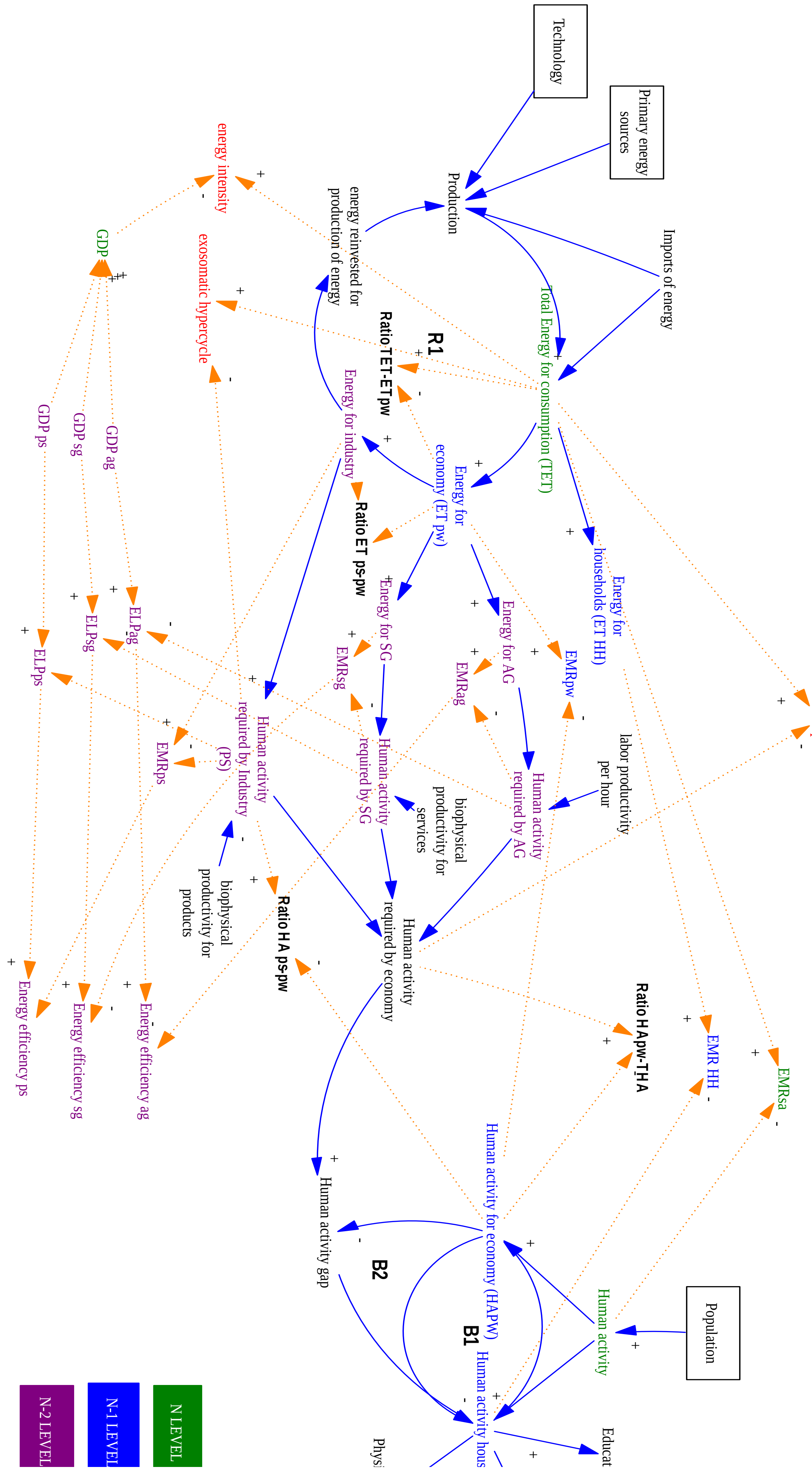
- ✓ The variables in green are showing the variables considered to study the metabolism of the National Level (N level).
- ✓ The variables in blue corresponds to the functioning of the productive and non-paid sectors of society (N-1).
- ✓ The purple variables respond to the disaggregation of the economic sectors (N-2). At this level we can observe indicators resulted of the labor productivity and energy efficiency of

each sector. Also, the human activity requirement by a sector that is result of the productivity of the sector and the amount of energy used in that sector within MuSIASEM way of accounting.

No information on how exactly the shares of energy in each economic sector are functioning or how the demand the productivity variables might change according to the socioeconomic conditions or other factors.

The Human Activity component and the Energy transformation processes besides being the most elaborated in the accounting system are also the most significant towards a sustainability assessment base on the feasibility, viability and desirability of the societal metabolism pattern of a society.

The next chapter is dedicated to the development of two SFD structures in order to understand these two components of MuSIASEM from a dynamic perspective



Figur 21 Causal Loop Diagramm (CLD) with variables and indicators on Argentina's Case based on MuSIASEM literature.

Chapter 5

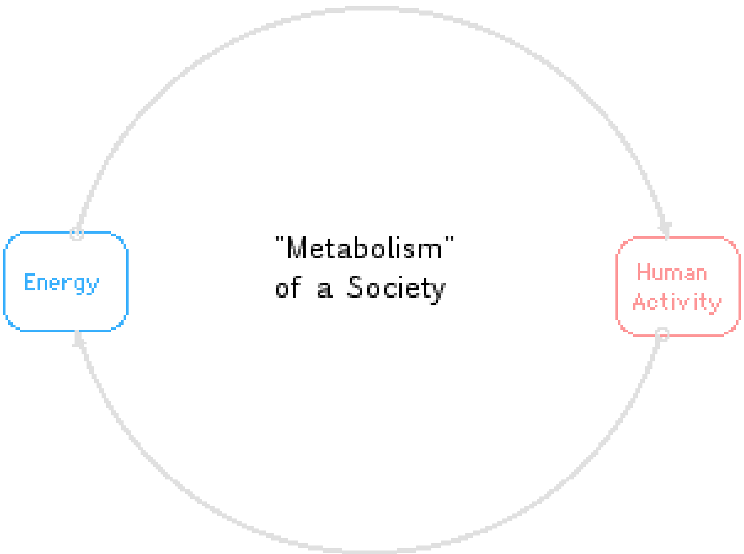
Modeling key issues in MuSIASEM framework

Human activity and Dynamic Energy budget

Modeling key issues in MuSIASEM framework

The current chapter is dedicated to perform two modeling exercises on the key points of MuSIASEM to explain the societal metabolism of a society: *human activity* (HA) and energy. This was done in order to test the MuSIASEM framework, given that it was not possible with the information from the application case due to the gaps in information presented in the previous chapter.

These modeling exercises will be mainly guided from the MuSIASEM literature: "*Energy Analysis for a Sustainable Future: Multi-scale integrated analysis of societal and ecosystem metabolism*" (Giampietro et al. 2013) and the publication by the Food and Agriculture Organization from the United Nation's "*An Innovative Accounting Framework for the Food-Energy-Water Nexus: Application of the MuSIASEM approach to three case studies*" published on October 2013. Synthetic data was used to run the modeling exercises.



According to MuSIASEM, societal metabolism is:

> *"Notion used to characterize the processes of energy and material transformation in a society that are necessary for its continued existence, sustainability or Autopoiesis. In order to maintain this, those transformations cannot overpass the thresholds posed by the Ecosystem Metabolism. Both, societies and ecosystems are levels of a Hierarchical System. In them, there are relations that have to be maintained within and among the levels, including the relations that control the biophysical transformations, or metabolic patterns. The metabolic patterns of the social level of a hierarchy depend on its internal and external relations. They pose internal and external constraints to the autopoesis of the system." (Giampietro et al. 2011)*

The Exosomatic Metabolic Rate (EMR) is measured in the framework by a ratio between the Total exosomatic throughput, which is the *total energy consumption,* and the *human activity* of a certain level of the society. In other words: Energy consumption / Human activity. In line with the definition provided from the literature, the sustainability assessment made possible by this methodology is through the desirability, viability (regarding internal constrains) and feasibility (external constrains) checks of the metabolic pattern of the society. Therefore from a SD perspective, understanding the dynamics of what they call the Energy dynamic budget and of the HA component, becomes fundamental to this sustainability assessment.

During the modeling process of these two structures, different tests were performed; i) structural tests: which check if the structure of the model is an adequate representation of the real structure theoretically and empirically and ii) behavior tests: which check if the model is capable of producing an acceptable output behavior, specifically pattern prediction and extreme conditions tests (Barlas, 1989).

The theoretical structure tests were performed by checking the correct interpretation of the principles of MuSIASEM in the model building process and its coherence with the equations provided. The empirical structure tests were performed by taking snapshots of variables categorized as funds to make sure if those were suitable for a SD model.

The behavior tests were performed by checking the coherence of the model results, with what the framework applications are expected to analyze, and if the model was generating the expected outcomes. Also, extreme condition tests were performed to check the coherence of the structure under extreme situations. It is important to say that the behavior tests were just performed in the modeling exercise that had a running model as an output, the other structure presented limitations in the information provided in the literature.

In the next section, these modeling exercises will be explained in detail. The equations of each model structure are in the appendix section of this document.

Human activity

It refers to the *human activity* measured in hours obtained considering the total of the population times the hours existing in one year. This time is allocated into paid work activities or households activities depending on the demographic composition and socioeconomic characteristics of society.

The paid work is divided into human time allocated to agriculture, service and government, industry, or energy and mining sector. The household time allocation is divided into leisure, physiological overhead, and education activities. It is considered that the time that is not assigned to paid work will be assigned to leisure time and in case the economy requires more labor time, this time will be taken from the leisure activities of people.

The modeling exercise on *human activity* component is expected to explain the next questions:

1. What is the structure explaining the dynamic change of human activity in the society?
2. What are the factors driving the allocation of human activity in the society?

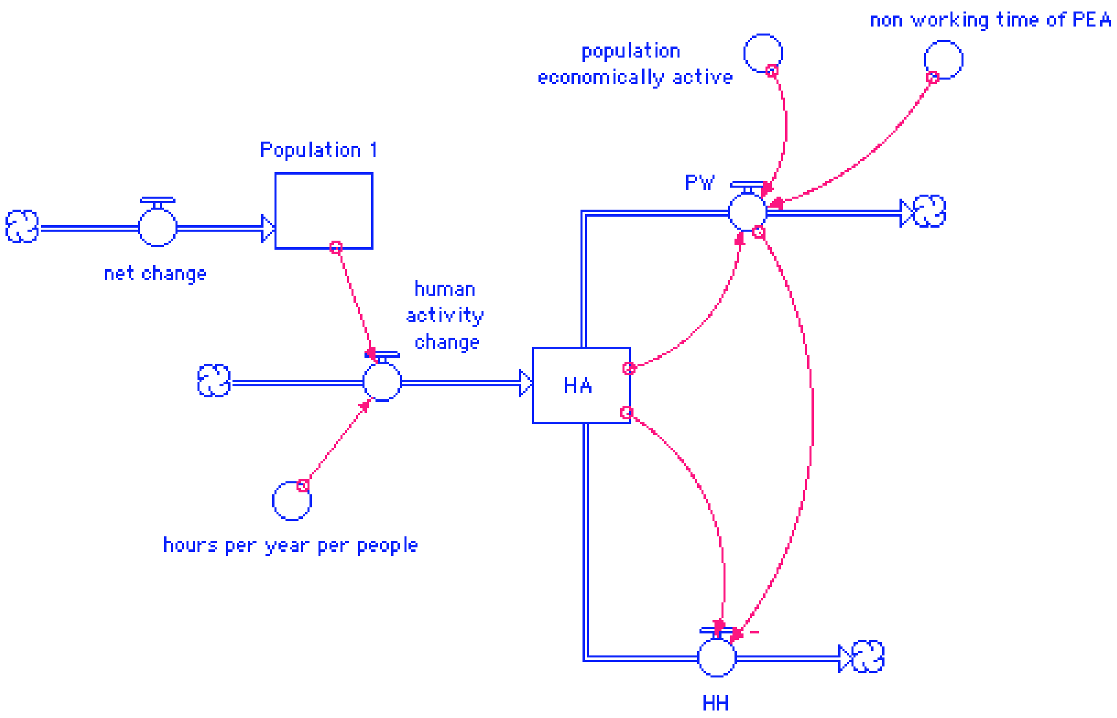
The first challenge presented in the modeling activity is the consideration of *human activity* as a fund. If we recall, these definitions of funds and flows are appropriated from Georgescus Roegens' model, and they refer to the following definitions:

> ***Funds***: are the elements that remain regardless all transformations in the system during a period of time. Funds have the capacity of transforming input flows into output flows during

the time scale of the representation and preserve themselves. They can be used only at a specified rate and are periodically renewed. Examples: land, population. Within MuSIASEM approach the fund responds *to what the system is made of*.

Flows: elements that disappear over the duration of the representation, they can be an output without ever having being an input or vice versa. Flows in this case can be matter or energy controlled or dissipated. The size of these flows depends on internal (capacity of processing a flow, for instance, technology) or external (availability of an stock of a natural resource) factors. Within MuSIASEM approach the flow responds to *what the system does.*

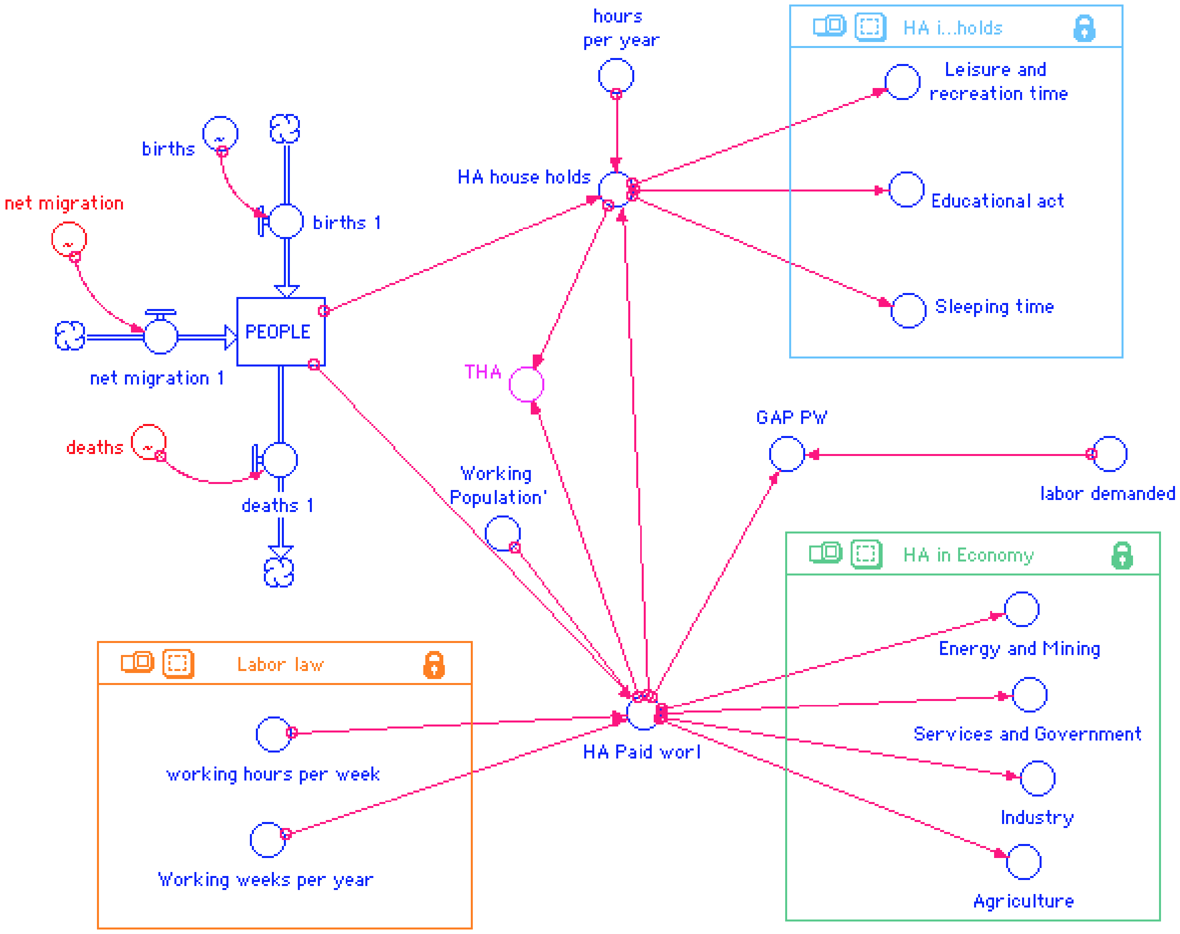
Even when the equation *HA = Population * hours in a year per person* should logically give the right number of the total human activity to allocate in the paid work sector or households, considering *human activity* as a fund is problematic.   *HA* it is considered a product of the total number of people and the time each of them can dedicate to perform activities in a year, therefore it is measured in hours per year. From a SD perspective if we try to make a snapshot of the *human activity*, it is hard to picture how exactly that would be done because as previously described, human activity encompasses a diversity of activities within the paid work sector or in the households. It is also not something that can be accumulated, *human activity* as it is measured by the time in a year in hours, is theoretically passing as time progresses. Therefor it can't be accumulated, the time that is not invested in an activity in the present cannot be allocated to paid work or any other activity further on. If we try to model *human activity* as a fund, we will have a structure like this one:



Figur 22 **SFD Human Activity as a fund**

In the former structure we can see HA as a fund. If it was a fund, the flow would be determined by the number of people and the hours per year per person; it would be an instantaneous and continuous valuation. So it does not make any sense to model it this way because *human activity* is not accumulated, and measuring the change in human time in a given period (time per year) provokes inconsistency in the analysis and the units of the model. According to Barlas (1994), in order to consider valid an SD model, the system structure should be valid and not its behavior. The model should show the "right behavior for the right reasons".

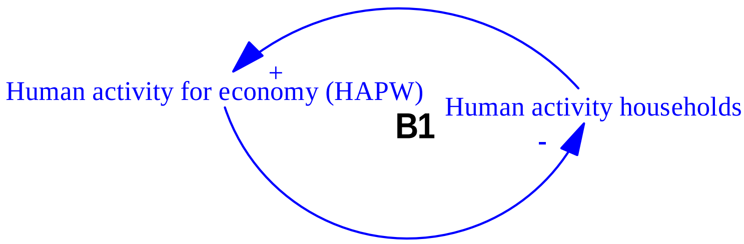
The following is a reinterpretation of MuSIASEM's view on *human activity* using SD methodology, taking into consideration the units used for its accounting:



Figur 23 Structure of Human Aactivity as a variable, Population as a fund

This structure shows how population is the fund where *human activity* derives from. Changes in *human activity* initially respond to changes in population, which is the fund. Secondly, the changes in *human activity* will respond to the socioeconomic organization or characteristics. This model structure shows the labor time allowed per week, to demonstrate an example of how other variables could change the HA in paid work. The structure shows unit consistency and a coherent behavior with the loop elicited from the narrative, even when in the narrative HA is considered a fund. Later on we will discuss how this has implications for a sustainability assessment. The gap variable in the model suggests a possibility of creating a policy in order to fulfill the needs of a labor requirement.

This can be a point of further development on the framework that will activate the other balancing loop elicited in the CLD developed, as shown in figure 20 of this document.

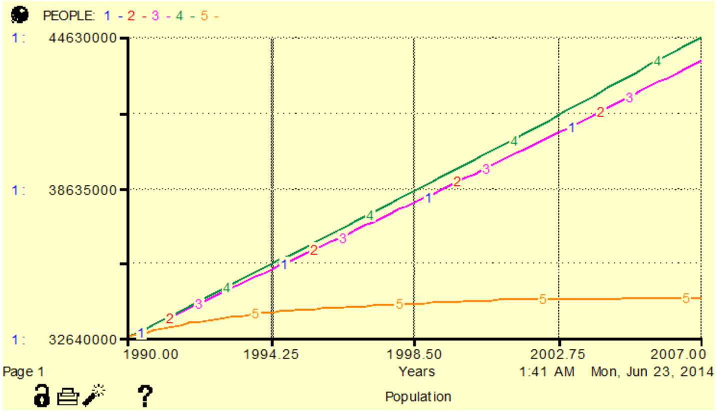


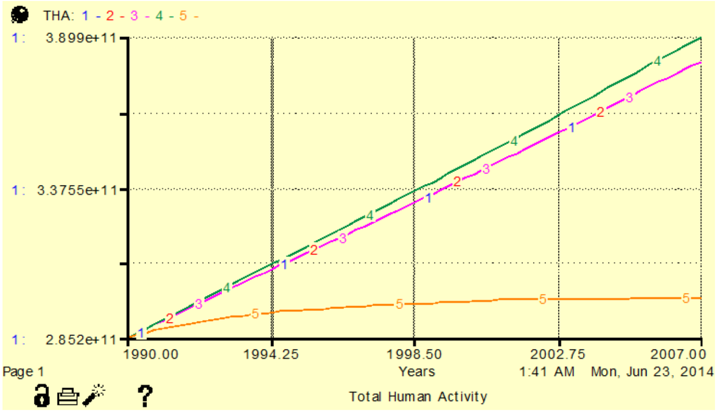
Figur 24 **Human Activity Paid work (HAPW) and Human Activity House Holds (HAHH) balancing behavior**

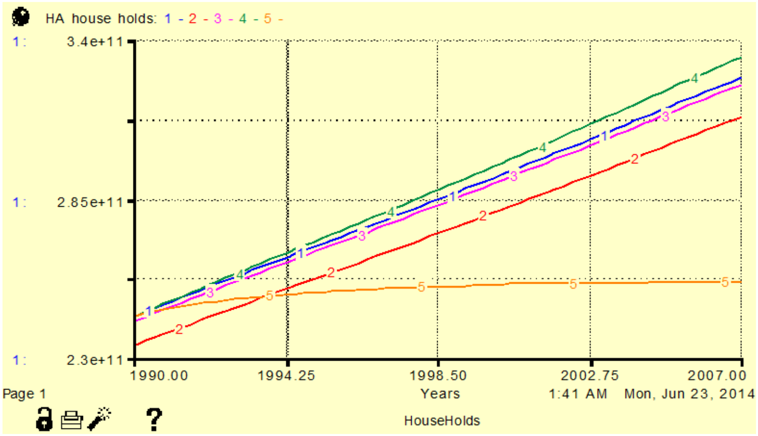
As well, if we run the model, we can see how the HA variable is responding to changes in population. These simulation runs were part of the tests performed on the prediction pattern and extreme condition tests. The changes in population are determined by the change of its flows: births, deaths and net migration. In this case, if we want to see how the HA changes according to changes in population, the most immediate changes will occur through a change in the migration rate or deaths. The next comparative graphs show the HA in paid work and households, Population and Total Human Activity behavior in the following cases:

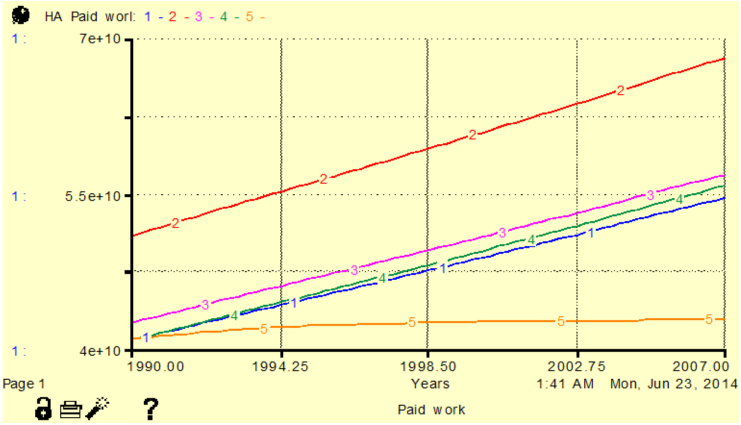
1) Run 1 Normal state: 48 work weeks in a year; 40 working hours per week; deaths of 80,000-100,000 during the period of analysis; births at 700,000 per year during the period of analysis; migration rate at 50,000 per year; an initial Population value of 32,642,000
2) Run 2: Increase of the working hours per week by 10 hours
3) Run 3: Increase of the working weeks per year by 2 weeks
4) Run 4: Increase in the immigration rate
5) Run 5: Increase in the death rate

As we can observe in the next graphs, *human activity* responds to the changes in population. The *human activity* allocated in paid work presents a more significant increase when the working hours per week are increased, than with the working weeks per year. These kinds of changes can be experienced by modifications of labor law, or by demand of the socioeconomic system. When considering HA as a variable modified by the fund Population and other variables of the socioeconomic system, a better understanding of the elements that modify societal metabolism can be obtained. This perspective also increases the possibilities for a sustainability assessment, given that is not just a snapshot or indicator's development what will determine the "sustainability" of the energy use pattern. It is instead a more specific observation on the change of funds, in order to know which components of the system are leading the other changes in the system over time. The former interpretation might be not the only one possible to model the HA component of MuSIASEM, but it results are useful for the analysis (Barlas & Carpenter, 1990).









Dynamic Energy budget model

"In the study of any phenomenon our first inquiry must be: how can this phenomenon be explained as a transformation of energy? What is the original form of energy? What is the final form? What are the conditions of transformation?" Maxwell , 1877

As explained previously, the societal metabolism notion is obtained by Energy consumption / Human activity. The energy consumption in a society is a process that occurs due to several factors, among them is population, socioeconomic structure, resources to produce or import energy, and availability of natural resources. According to MuSIASEM, a society allocates certain amounts of energy within different levels of society. The amount of energy a society can allocate per year is result of a complex process of energy transformation stages, where the primary energy sources go to a production process, and ends at the final energy for consumption stage in a different energy form. Each of these stages within the transformation process presents different conversions coefficients, plus transformation and distribution losses, until it finally becomes energy available for consumption. This dynamic energy budget is under external constrains, meaning that if the primary sources are coming from fossil fuels, the energy available for society depends on the availability of this non renewable energy source. The final units of the energy available for the consumption of society are measured in joules of mechanical or thermal energy, with MuSIASEM accounting for several transformation steps in order to ensure the unit consistency along the process.

The SFD structure built using the MuSIASEM narrative is expected to provide explanatory capacity on the following questions:

1. What are the factors limiting the amount of energy that can be used by a society to express a given set of useful functions?
2. What is the structure characterizing the dynamic energy budget of the society?
3. What are the factors limiting the total throughput of energy associated with the external constrains? What are the internal constrains?
4. What are the causes of the change in the energy budget, i.e. ability to maintain the required power capacity or to control the relative flows of applied power?

In MuSIASEM literature, in order to define the performance of the energy transformation processes, it is required to consider integrally and simultaneously the set of gross energy flows, the resulting set of net energy flows, and the relative set of end uses. In order to consider different energy forms used in the society during all the processes of the energy transformation chain, the conversion factors are important in this assessment, i.e. the caloric value of fossil energy in tons of oil. Nevertheless, it alerts that when using the conversion factors along the accounting, other implications of the quality and nature of each energy type can be minimized. MuSIASEM also stresses the importance of the time dimension associated with the energy flows; the power capacity is able to convert energy input into useful energy in a given period of time.

One of the limitations on the narrative understading was the hypercycle. According to Giampietro et al. (2011), the hypercycle part is a mandatory feature of any self organizing system, and in this case is a loop in charge of generating a net surplus of the production factors: power capacity and energy carriers. And it is described in this way by Giampietro et al (2013).: "*the part generating the hypercycle has a positive net return in energetic terms when considering its interaction with the context. Indeed, it expresses a ser of activities aimed at gathering energy inputs (primary energy sources) from the context and making critical inputs available to the rest of the system… This part thus make available to the system more energy carriers, power apacity and material flows than it consumes for its own operation."* Also, taken from Ulanowicz, the authors state that when hypercycles operate without a coupled process of control, they do not survive for long. Also, this hypercycle part is considered to be essential for long term sustainability and it is this part that is in charge of the adaptability and stability of the metabolic system in the long run (Giampietro, 1997). The next figure is a standard grammar of the understanding of processes where the primary energy sources and energy follow in order to become useful energy.

Another way of understanding the hypercycle is provided by Greer (1995) "*In the absence of effective limits to growth, once started, this expansion becomes a self-reinforcing process, because additional capital can be brought into the production process, where it generates yet more new capital, which can be brought into the production process in tur*n."

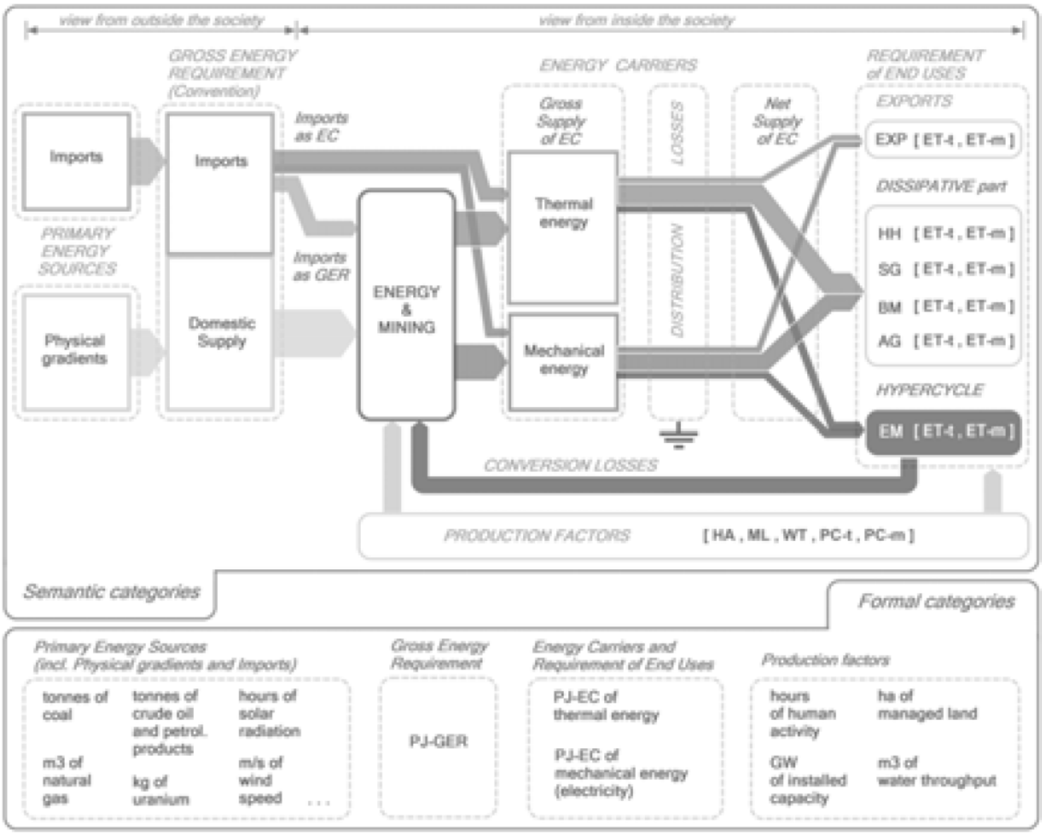


Figure 3.1 The "standard" energy grammar used for assessing the energetics of human societies – Relation between semantic categories and formal categories used for the accounting of energy flows in the metabolic pattern.

Figur 25 **Standard energy grammar extracted from "The viability and desirability of alternative energy sources: the controversy over nuclear power" by Francois Diaz Maurin, 2013.**

In SD terms it seems to be talking about a positive feedbackloop. Nevertheless, in the energy analysis literature of MuSIASEM it is not clear how this hypercycle works in the energy transformation processes context. Here we understand how the hypercycle is part of the production factors. Although, as this is a new way of accounting, we are not sure on how to model this according to the narrative because it might depend on other characteristics of the socioeconomic system and the technology available. It could be modeled with synthethic data in order to have an approximation of how the processes work and how the dynamic energy budget might be developing and influencing the whole metabolism of society. It is mentioned that the hypercycle part of society and the dissipative part of society complement each other, the hypercycle part could not be stable without the dissipative part, they guarantee functionality of the system as a whole. The dissipative part is the component that makes society capable of fulfilling its functions.

The relation of the hypercycle part with the dissipative part of the society might also depend on the characteristics of that certain society. Altough, with a prototype of processes in a society we could gain insights into the relation between the energy consumption in a society.

While building the structure of a SD model using the available literature on the dynamic energy budget, it was a matter of constructing the simplest SD model. The decision to make it was based on a hypothetical situation where a country just relies on thermal energy to fulfill its functions; this kind of energy is derived from fossil fuels. This decision was taken in order to assure unit consistency in the process, using the conversion factors of this type of energy with a set of primary energy sources: oil and coal. It was decided that the energy carrier in this model was only going to be electricity, assuming that society works on just electricity as a final energy.

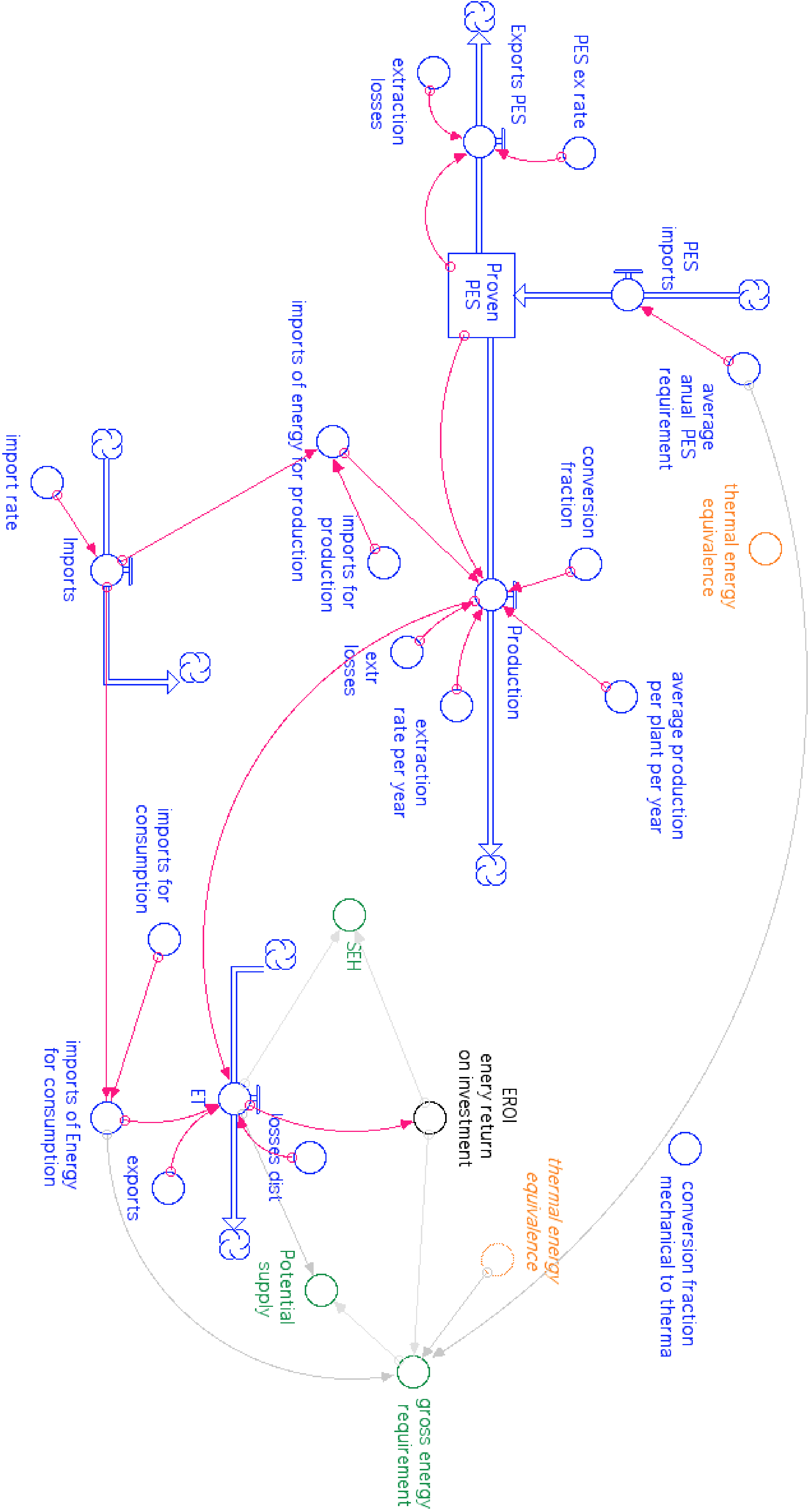
As well, in the literature and energy grammars developed using MuSIASEM the energy transformation process is described without the existence of any stock of energy, it always refers to flows of energy. Nevertheless, the transformation process from tons of oil to thermal joules and electricity happening within flows is not very precise to model it. In SD terms, the stock defines the identity of the flow that modifies it. In order to develop a proper SD model on the dynamic energy budget of a society more information on the process of the energy transformation is required.

In this model structure the gross energy requirement was calculated according to literature by the import of primary energy sources, energy carriers and the EROI (energy return on investment). Although with this last variable, there is not enough information to find out how this could be calculated within MuSIASEM because of the reasons explained formerly. The other factors defining the fraction of energy that will be assigned to the production of energy depend on characteristics of that society like the quality of energy technologies, plus it might imply the consideration of energy carriers of different types, energy flows of different levels which at the same time require different production factors such as human activity or power capacity.

In order to build a SD model it is important to make the boundary definition on which kind of physical gradients and energy carriers will be considered in the analysis. Therefore it is important to characterize the system identity regarding its energy transformation system so as to define its power capacity. This will determine the amount of energy that could be generated in a given period of time, regarding also the availability of the primary energy sources mix. The variable SEH is referring to what they call "strength of the exosomatic hypercycle" which means the ratio between what is reinvested in the energy production of the final energy for consumption, coming from the EROI. SEH shows the ability of delivering a certain amount of useful energy to the society, per unit of useful energy required to run the production of energy. From a societal metabolism perspective where human activity time matters, the higher this ratio is, the larger amount of labor time that can be used in other activities by society. Within the energy system it will also be about the efficiency of the energy system.

The next structure was built with the information available on the dynamic energy budget and the accounting ways of its main indicators:

The variable called Potential Supply refers to the amount of primary energy sources required to produce the net energy supply for the society. It might also have implications depending on the context of energy production and which are the primary energy sources, like in the power capacity used to handle investments of energy input needed to replace human labor to obtain the same supply of energy carriers. This variable is used within the framework to analyze the quality of alternative energy sources.

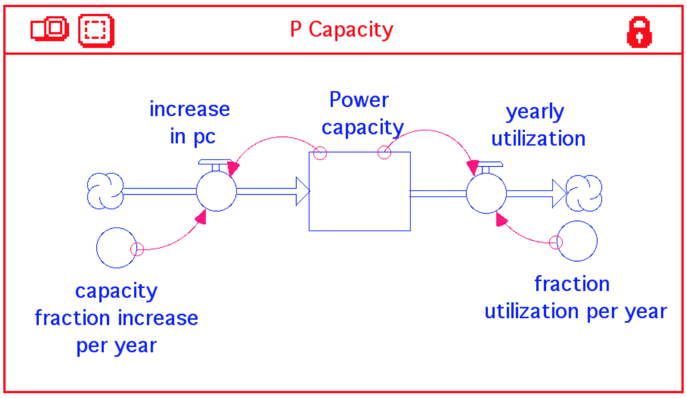


Figur 26 **SFD of Dynamic energy budget structure built of the MuSIASEM literature.**

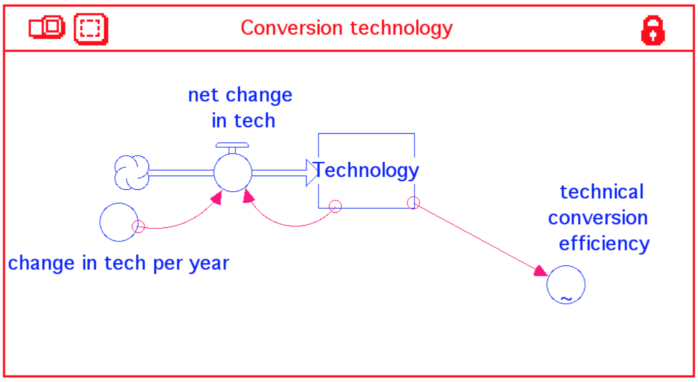
This model structure could not be run because of the lack of information to accurately interpret the hypercycle functioning. The simplest intent in modelling and simulating the hypercycle, was to consider just the energy requirement for the energy production process. However in SD, a flow influencing another flow directly is not possible to model. The framework talks about an instantaneous effect and this does not make sense from a SD perspective. Also, the interpretation of the MuSIASEM literature suggest more complex processes of this hypercycle functioning.

Besides the lack of specific information on the hypercycle component of the dynamic energy budget, another main limitation of this model structure could correspond to the interpretation of MuSIASEM literature available; it might be biased by the lack of knowledge on energetics of the modeler. This issue could be faced when policy makers or other researchers try to apply MuSIASEM.

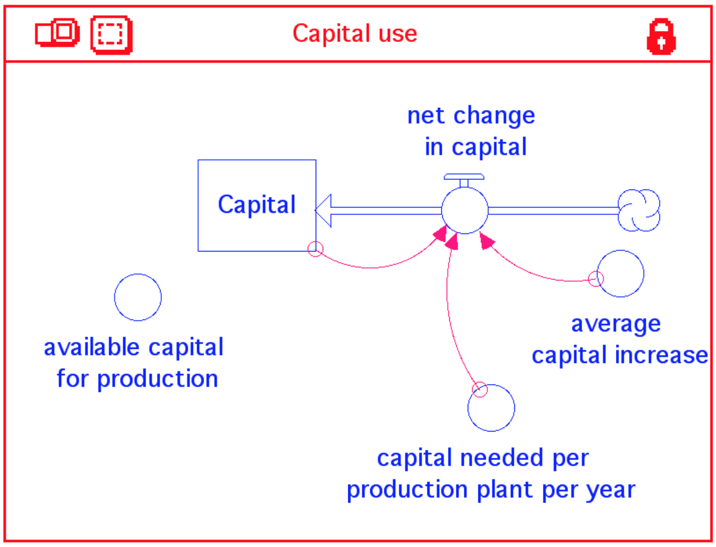
In the literature, there were mentioned the following factors of the production process and interpreted as stocks from a SD perspective. What it was desired to express here is that these production factors are not static and have their own flows that make them change, which at the same time depend on variables not develop yet in the analysis. The point here is to exemplify how the final energy available for consumption is driven by constantly changing production factors.



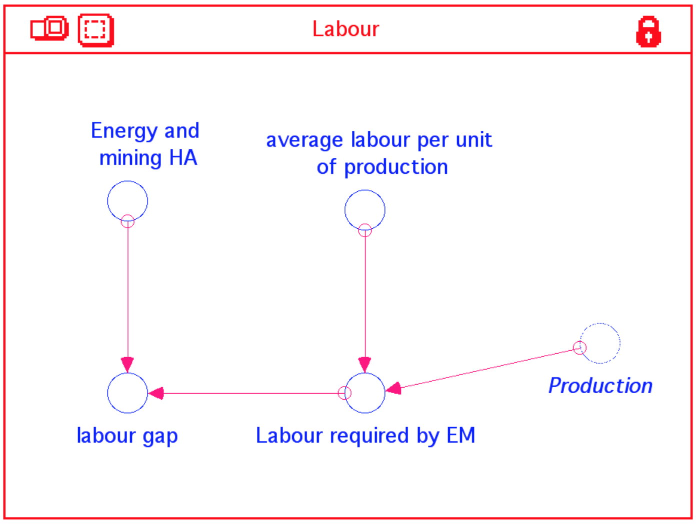
Figur 27 **SFD Power capacity change.**



Figur 28 SFD Conversion technology change.



Figur 29 SFD Capital for energy production.



Figur 30 SFD on Labor requirement by the Energy and Mining sector.

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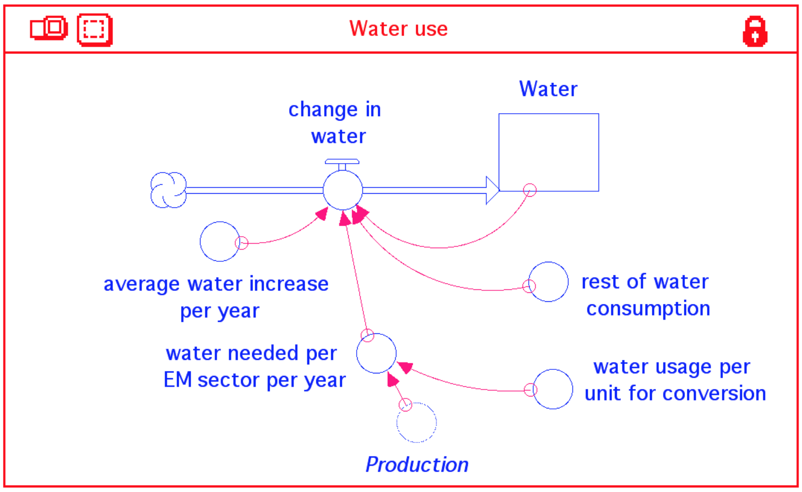
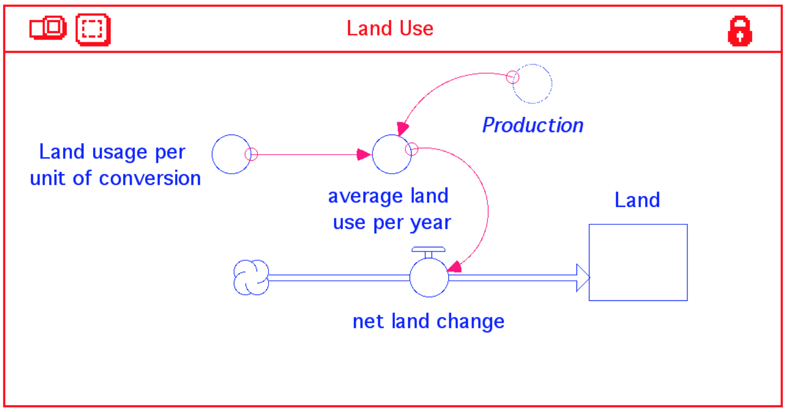
In the literature on the dynamic energy budget, the impact of the energy system processes on the water and land use in the society was also mentioned. The simplest way of addressing this from a SD perspective would be the following:



Figur 31 **SFD Water use.**



Figur 32 **SFD Land use.**

An energy analysis should provide a better understanding of the metabolism of a society, based on the *human activity* allocation and the energy use of the socioeconomic structure of that society in relation with its external constrains. Until this point it was not possible to simulate a hypothetical situation of the energy dynamic budget, in order to gain an understanding on how the societal metabolism indicators are susceptible to changes in some variables within the system. Nevertheless, there were elicited some insights of the processes implied by this bio-economic perspective on how society is functioning embedded in a biophysical environment. In this sense, there are some feedback insights gained of these exercise between MuSIASEM and SD and for a sustainability assessment, which will be covered in the next chapters.

Chapter 6

Validity of MuSIASEM from a SD perspective

Validity

"*Extent to which data collection method or methods accurately measure what they were intended to measure and the research findings are really about what they profess to be about*".

Saunders & Lewis (2012)

Conceptual approaches between SD and MuSIASEM

"What is the same when everything is different?"

There are substantial conceptual issues shared between SD and MuSIASEM approaches. In this section we will talk about two of them, the first is the fund and flows categorization and the compatibility of MuSIASEM with the SD principles according to Forrester (1968).

In MuSIASEM approach flows are characterized in relation to their funds, for instance, energy consumption per year per capita, water consumption per hectare. It states that if a variable is considered a fund within a boundary of definition and scale it should remain like that during the analysis exercise performed. According to Giampietro et al. (2009), it is a choice made by the analyst on how to manage the perception and representation of metabolic systems that are evolving in time because they consider that evolving metabolic systems express a series of expected patterns of energy transformations simultaneously but at different scales, the change in scale can result in a different categorization of a fund or flow according to the scale and boundary selection. Until this point, it presents a similarity with what is understood as a fund and flow in SD terms. From this categorization, when properly applying the right units and a coherent model structure for a dynamic analysis, using SD is possible

Nevertheless we found some differences in the way these categories of variables are managed. In MuSIASEM it is considered that a fund responds to the question "what a system is" and the flow to the question "what the system does". This interpretation in SD terms is not that simple because it can cause confusion even within the same scale of analysis. It was found that *human activity* is considered a fund in MuSIASEM and the application cases reviewed, but analyzing this consideration from a System Dynamics perspective we found that is does not match with Georgescu-Roegen's funds definition as explained in chapter 5. Within the SD literature there are different forms of test on the structure of a system, for instance, a fund or stock should be able to be observed by a snapshot test in a certain moment of time, also, SD literature tells us that stocks are the memory of a dynamic system, can decouple or change the shapes of the flows and create delays (Forrester, 1969).

In order to get a more accurate analysis of the relation between conceptual approaches of these two frameworks, it is important to recall the twelve SD principles according to Forrester (1968) extracted from Zock (2004). The next chart shows an assessment made after the MuSIASEM literature revision and the modeling exercises.

SYSTEM DYNAMICS PRINCIPLE	MUSIASEM
1. Closed boundary: dynamic behavior arise within the internal feedback loop structure of the system	Compatible MuSIASEM states different societal levels in order to analyze the metabolic pattern of society. Within each level there are variables to take into consideration. At level N-2, N-3 and N-4, we found narrative that talks about the existence of what they call an "hypercycle" that takes part of the material and energy flows available for consumption, again to the production process to keep the

	material and energy flows production. This hypercycle could not be explicitly modeled because of a lack of specifications on what stocks or flows it is related to.
2.Feedback loop as structure element of the system: causally closed path coupling system state, observation of this state and decisions based on this information. Dynamic behavior is generated from the feedback. Complex systems are assemblies of interacting feedback loops.	Compatible Loops are elicited from the narrative (see figure 21) but the dynamic component has not been developed in the application cases or the tools used of this approach.
3. Decisions within feedback loops: decisions control actions that alter the system levels that at the same tie influence the decision. A decision process can be part of more than one feedback loop.	Compatible There was found a possibility to close an open loop within the Human Activity sector in order to develop policy (Example: Figure 20, B2 loop).
4. Levels and rates as loops substructures: a feedback loop is conformed by levels (states or stocks) and rates that can be altered by other variables.	Compatible It uses Georgescous's fund and flow model to categorize the variables within the analysis. The rates are mentioned in the narrative to be susceptible to other variables of the socioeconomic system.
5. Levels are integrations: levels or stocks are variables that cannot change instantaneously and they accumulate or integrate according the results of actions in the system.	Compatible. Theoretically, by using the Georgescus Roegen's categories, it is understood that funds are integrations. Nevertheless, MuSIASEM has not addressed yet a way of making its analyses dynamically.[9]
6. Levels are changed only by the rates: the previous level is altered by rates that flow over the intervening time interval.	Compatible and aligned with Georgecus Roegen's model and the right selection boundary definition.
7. Levels completely describe the system condition: just values of level variables or stock are needed to describe the condition of a system.	Compatible. In MuSIASEM the levels or stocks responds to "what the system is"
8. Rates not instantaneously measurable: no rate can control another rate without an intervening level variable.	Unexplored. Specifically in the hypercycle explanation it is not clear if this could be a flow modifying other flow in a given period of time or how does it work.
9. Rates depend only on levels and constants: no rates depends directly from another rate, no rate equations of a system are of simple algebraic form, don't involve time or solution period, they don't depend on their past values.	Unexplored. MuSIASEM narrative does not provide explanation on the changes of all relevant flows driving the dynamic energy budget processes or equations or further elaboration on how rates are modified.

[9] In MuSIASEM literature has been described the intentional avoidance of using mathematic assessments related to the critique to prediction aims of complex system features. It is considered that the factors and variables of the system are changing constantly therefore it is not desired to use a deterministic tool to address the dynamic adaptation capacity of complex systems.

10. Rate substructure or system sub-sub structure or goal, observation, discrepancy, action structure: a policy or rate equation recognized a local goal towards a decision point, the difference between the desired point and the actual state is the discrepancy which is used to guide the dimension of the action.	Compatible There has been identified an opportunity to extend the *desirability check* in order to regulate the allocation of human activity in the economic sector and households as a policy or establish a mechanism of control depend on the purpose of the policy. (Example: it could be a policy to respond to the labor demand in a period of time until a threshold to not affect the education or leisure activities).
11. Level variables and rate variables must alternate: any path trough the system structure encounters alternating stocks and rates.	Unexplored. MuSIASEM does not picture a complete system structure; nevertheless, out of the narrative preliminary system structures could be built that presented alternation between stocks and flows.
12. Levels and rates not distinguished by units of measure: the units of measurement of variables do not distinguish between levels and rates. The identification should clarify the difference between a variable created by integration (level or stocks) and the ones that are a policy or a flow in the system (rates) feeding the levels.	Compatible but not described as such. MuSIASEM framework stresses the importance of unit consistency because of the relevance of in order to have a proper accounting on how funds are changed by the flows. MuSIASEM does not talk about integration as characteristic of funds or stocks but it mentions that funds should be conserved during the analysis boundaries and its flows should be able to maintain them. In sustainability terms it also mentions that the system funds have to be maintained.

Validity of MuSIASEM framework in the light of a sustainability assessment

Critical perspective to MUSIASEM framework

MuSIASEM provides a narrative to assess sustainability by developing indicators related to the energy use of society in relation to the allocation of human hours to paid work and household activities (non paid activities). In other words, how much energy is being consumed and how much human time they are putting in the economy to fulfill its functions, this is what they call metabolism. The energy consumption per human activity is just an indicator of the “metabolism” but it implies taking a look at the economic composition of the society, and within the economic sector, the productivity of each economic activity. This depends at the same time on other factors, such as its economic development or technology available.

In the same way, the human time available to allocate in households activities or paid work depends on the population composition, which is a product of the migration flows and the deaths and births in the country, and on the age composition of that population, from where the dependency rate is also obtained. Human time will depend as well, in a formal perspective, on the structural normative on the labor regime of the country, while in some other countries this could depend complementarily on the informal structures that allow people to work beyond the regulation of laws.

MuSIASEM does not provide an explanation on how things change over time, yet it provides categories to assign units to variables all in coherence with the final goal of analyzing the energy use indicators. What MuSIASEM does, is to focus on the assessment of the structural components and functions a society performs, and from this it develops indicators based on economic and biophysical variables without addressing how things change over time.

In the Chapter "*Studying the feasibility and desirability of the metabolic pattern of society from withi*n" it explains that MuSIASEM provides a way of characterizing the network of energy transformations taking place in modern societies using the multilevel matrices of data arrays. It attributes to this integrated representation, of what they call the metabolic pattern, across levels the capacity of generating robust analysis and scenarios in order to express what is not possible for that society, in terms of its external constrains and material standard of living desired. Regarding this point, it provides the capacity of defining these conditions of the feasibility and desirability, in relation to its internal constrains by analyzing the indicators.

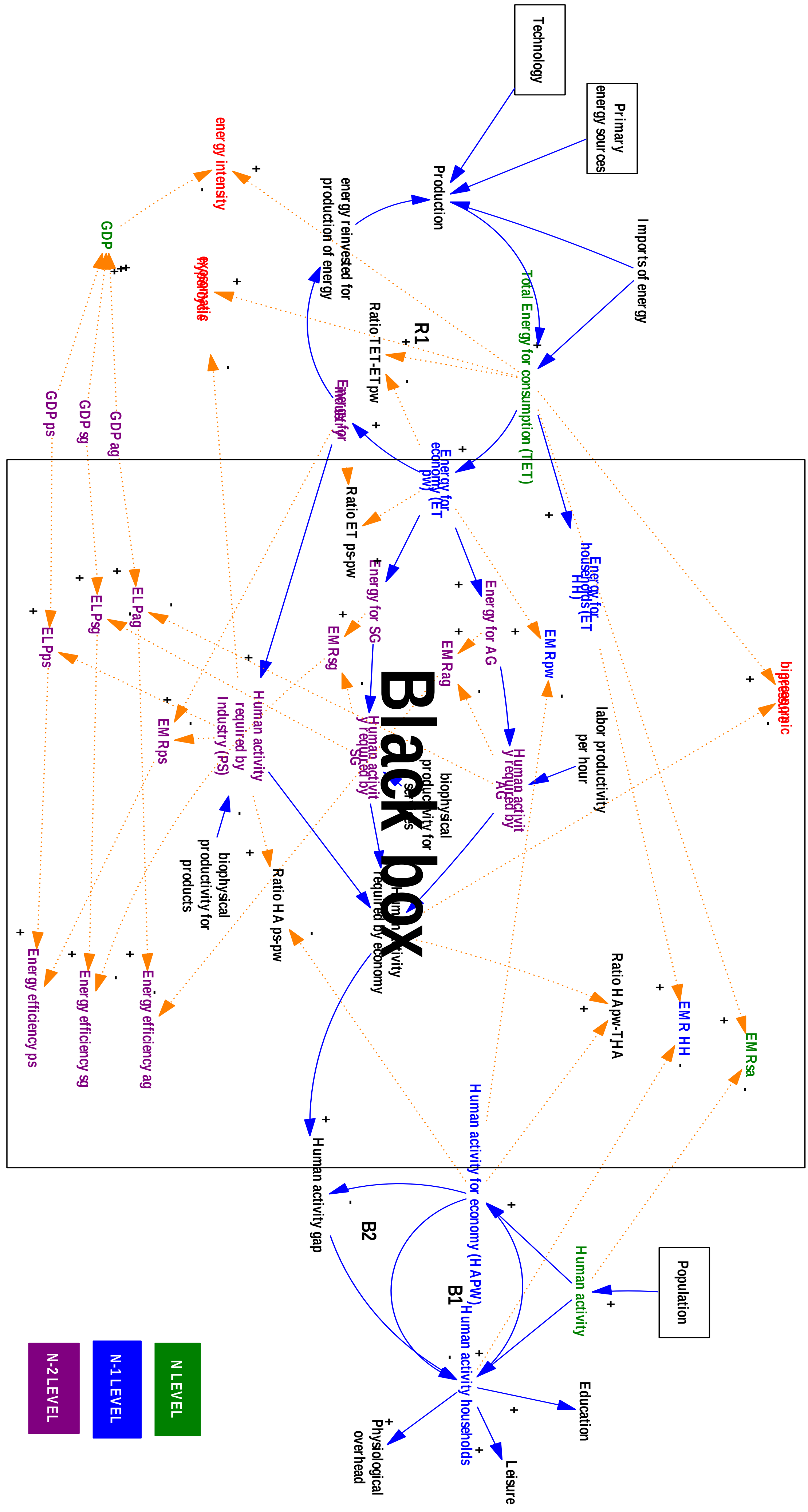
It is considered that the metabolic pattern of the society can be explained by the existence of an increasing effect of mutual information among the characteristics of the socioeconomic compartments, which influence the ratio of human activity and energy consumption, interacting across scales within a complex autocatalytic process. This talks about a unique way of self-organization with information and material feedback processes.

Once the integration of this is made, the viability and desirability of the metabolic pattern in consideration of the development of each sector of the economy is doable. But again, it will be matter of very general assumptions on what to be changed, regarding looking at the funds or flows as part of the structure of the system. Nevertheless, questions like the one addressed in this chapter: "*what type of changes would be required in the society (re-organizations of organs) to cut 50% of the actual energy consumption*?" or *"what type of changes in technology would be required to guarantee the viability of the resulting dynamic budget*?" could not be answered by the indicators assessment. They would require specifically a dynamic assessment on how each societal level is working. The authors of the framework state "*It is important to acknowledge that by using the protocol of analysis described in this chapter we can only develop quantitative characterizations in relation to what happens inside the black box*"

SD methodology principles could provide more specific proposals to the previous questions in order to clarify what they call the *black box*. This is understood as the dynamic processes inside the society that explain the consumption of energy, composition of economy, population change and supply of human activity, and so on. If a SD model is to be constructed using this methodology, MuSIASEM provides accounting categories and units for those variables and it explains how to make an accounting between different hierarchical levels.

MuSIASEM as a narrative is considered a qualitative improvement on energy accounting in comparison with traditional approaches. It shows two semantic categories: gross energy requirement and net energy carries across the societal levels and it provides a quantitative characterization of the pattern of consumption of different energy carriers in each societal level. This is in contrast to the current protocols on energy accounting, because by using this narrative new information and indicators on the energy transformations in national economies could be developed. For instance, the overall amount of energy required in order to have the final energy for consumption, which depends on internal constrains as the power capacity and technology of a country, and on external constrains as availability of primary energy sources.

In the next page we can observe the CLD elicited from the literature on the framework and where the black box is taking place within the narrative. The structure and drivers of the allocation of material, energy, and *human activity* requirement, plus allocation dynamics through economic sectors are not explained yet in the narrative as such. Each system for sure, at a local or national scale will present different characteristics in this ”black box”.



Figur 33 MuSIASEM blackbox.

One big challenge addressed in the book, also expressed to be out of the scope of the MUSIASEM framework and referred to as fundamental on energy analysis, is how to establish a relation between the gross energy requirement for expressing the metabolic pattern and the requirement of primary energy sources that are beyond human control, considered funds. In this case, SD could provide the possibility of linking, and characterize the relation between external constrains, internal organization structure of economy, population composition and its change over time, in order to see what is the relation between the gross energy requirement and the availability of primary energy sources that for sure, is changing over time.

"If we could know where we are and whiter we are tending, we could better judge what to do and how to do it" Lincoln, 1858.

Importance of indicators for sustainability assessment

MuSIASEM states to be a methodology to assess sustainability issues based on the feasibility, viability and desirability checks on the indicators characterizing the metabolic pattern of the society at different levels.

The importance of the indicators as explained in chapter 3 is that they show values according to the internal organizations of the society, (i.e., organization of economic activities, technology development, population composition).These indicators are belonging to different hierarchical levels N, N-1, N-2 levels, a characteristic that as we discussed in the first chapters, is an important condition in the sustainability assessment of complex systems.

Donella Meadows in her report to the Balaton group called "*Indicators and information Systems for Sustainable development*" expresses the importance of indicators in order to manage the existing differences in world views. She adds what these indicators, besides being factual, should be about: time, thresholds, efficiency, sufficiency, equity and quality of life. Those indicators should be about coherent information systems, which imply a narrative or understanding of the world that could be comprehensive with the acknowledgment of the socio-ecological systems we inhabit. She proposes the information systems must be organized in scales, from which the indicators are to be developed; decreasing the specificity and increasing the scale. Therefore, it is manageable to create, understand and support decision-making processes. As well, indicators might be useful learning tools that, according to Meadows, imply an evolutionary process.

MuSIASEM indicators meet some of these suggestions and could be considered milestones in a SD model building process. MuSIASEM does not explain all the details in the society processes, as we are going to see in the next section, but it provides a bio-economic narrative and indicators where an SD model can be based on. According to Meadows, indicators show what society, scientists or decision-makers value as important in a given moment of time, and they provide implicitly a world's view; in this case, a bio-economic assessment for sustainability is promoted.

Besides the importance of the indicators developed in MuSIASEM for sustainability, after analyzing the type of sustainability "checks" proposed by MuSIASEM, there were some ideas on how to improve these checks through a dynamic assessment using SD models

Proposal from SD to enhance the Viability, Desirability and feasibility sustainability checks

Sustainability check	MuSIASEM	System Dynamics
Feasibility	Coherence of the system with its external constrains or boundary conditions. It is evaluated by looking at the local supply and sink side flows Tool: environmental impact matrix.	System boundary selection and characterization of flows and funds within the boundary. Check the responses of the system to a change on external constrains through simulation exercises (tool).
Viability	Congruence across sectors of the requirement and supply of flows. E.g. data aggregated on consumption at the whole level should match with the supply at local scales. Tool: multi-level, multi-dimensional matrix	Open the *blackbox* and clarify the dynamics that create the requirement of human time and material and energy flows. Identify those variables or leverage points that question the viability of the system. Tool: Specialized modeling on the socioeconomic sector.
Desirability of viable scenarios	Comparison of the resulting metabolic pattern (flow/fund ratio) regarding the functions at a local scale with benchmark values of certain types of socioeconomic systems. Tool: comparing benchmarks of indicators between countries.	Close the loops to regulate and balance dynamics or make intervention on variables to increase or reduce certain effects. Tool: policy eliciting by goal or target selections and simulation trials to asses the effects.

Limitations of both approaches

What are the limitations and what can be done by a complementary application of the approaches?

As we have mentioned before, the analysis of the conditions of desirability, feasibility and viability is important and valuable for the biophysical component the development of indicators implies, but it does not say more on the variables and organization supporting the numbers with which the ratios are calculated. In this sense, its explanatory capacity presents a limitation given that it lacks the ability to explain how the system really works. Instead, out of already known values it provides a way of making calculations.

Explanation of societal processes under which those variables in real world are obtained is out of the scope of MuSIASEM. So, until now, the approach by itself cannot provide any practical recommendation to change what they call –the metabolic pattern- of the society. It is important to say that this was never promised by the approach but it clearly represents a challenge for any sustainability assessment. A sustainability assessment that ignores the dynamic component of complex system, and lacks ways to address how things change over time, can turn out to be insufficient.

SD methodology can provide insights in order to actually give a practical proposal for policy making or interventions in order give a practical sense to sustainability assessments. This can be achieved by developing modeling exercises, for example, i) on the change in population in order to satisfy the labor time requirement for a society considering the economic state and technology development of each sector and its contribution to the GDP, ii) the external constraints related to the dynamic energy budget, in other words, the possible development of the energy available for consumption given a fixed amount of primary sources and the technology, labor and capital investment for its production.

What can't be done?

If we recall what was discussed in chapter 2, Constanza (1993) states as important 3 issues on modeling ecological complex systems, one of them scale and hierarchy considerations already covered during the present work and developed also by MuSIASEM. But there are two other that were not discussed yet:

1) The application of the evolutionary paradigm.

About the application of the evolutionary paradigm, it is fundamental to say that neither SD nor MUSIASEM are capable of explaining any spontaneous endogenous change, in order to rearrange functions and activities based on the available funds. MuSIASEM talks about thermodynamics equilibrium but it does not explain how this will actually work within the societal context. The adaptative capacity given the critical organization of complex systems, also known as the Zipfs law, could express the existence of balancing or negative loops yet unknown or adaptations of the system individuals or organizations provoking emergent behavoir, for this, other modelling approaches would provide more possibilities such as agent based modeling (ABM).

Also, as stated by Dangerman (2014) SD mostly falls short in explaining the evolution of complex systems because is not really capable of letting new variables arise or disappear organically (as in real evolution) in its models. Further he explains that if in SD you want to have a new variable you need to build it in, and then you need to restart the simulation runs with that new model; so there is cut-off point between the first and the second model and their simulation runs, cutting what would be the organic evolution process.

2) Nature and limits of predictability

It is well known in the Systems Dynamics community that SD models are not prediction tools but rather tools for gaining system understanding in order to make strategic interventions. Every modeling activity has a lot of limitation because they respond to a selection of what the system is believed to be plus a high level of aggregation. A lot of variables are left out of any modeling exercise and there is always a boundary of what is known, for instance of the initial conditions of the system. These models could be seen and used as tools to generate scenarios under certain assumptions. Transparency in those assumptions is a crucial component. If those assumptions are close to reality the quality of the model outputs can generate insights of the system development, but again, always under the limitations already explained. In the other hand MuSIASEM clearly states to be a methodology without aims of prediction but rather provide indicators to evaluate the feasibility, viability and desirability of the metabolism of a society based on internal and external constrains. None of these disciplines, SD and MuSIASEM try to be predictive.

As a conclusion for this chapter, and recalling Saunders and Lewis definition, *validity is a condition of a method that measures what it intended to measure and the findings of it are about what it profess to be about*, MuSIASEM literature succeed at providing indicators of sustainability of the metabolic pattern of a society based on its internal and external constrains, so it fulfills its purpose. Nevertheless, from a SD perspective, it was discovered that MuSIASEM has to address some challenges in order to properly provide a systemic view consistent with dynamic system analysis. Some of these challenges are the right categorization of funds and flows and the detailed explanation of the main processes of the energy transformations it attempts to assess. The importance of a dynamic perspective of the metabolism pattern of a society could improve significantly a sustainability assessment. In this sense, we found several possibilities where SD can promote system understanding on the dynamics around the indicators brought by MuSIASEM. In the next chapter some proposal are going to be expressed in order to find some ways to overcome the challenges of the framework.

Chapter 7

Conclusions

"To build a model is to encode a natural system into a formal system, compressing a longer description into a shorter one that is easier to grasp. Modeling the nonlinear outcomes of many interacting components has been so difficult that both social and natural scientists have tended to select more analytically tractable problems (Casti 1994). Simple boxes-and- arrows causal models are inadequate for modeling systems with complex interconnections and feedback loops, even when nonlinear relations between dependent and in- dependent variables are introduced by means of exponents, logarithms, or interaction terms. How else might we compress complex behavior so we can comprehend it?"

Anderson, P. 1999

Conclusions

MuSIASEM, a tool for whom?

Currently the need of addressing systemically the nature and human dynamics within the present institutional and economic structures, with special care on external constrains like for instance resource availability, is a priority of policy makers globally. Examples of this are the efforts of organizations such as Nexus: The Water, Energy and Food security Resource Platform of the German Government [10]or the Food and Agriculture Organization from the United Nations. This last one is trying to create tools to assess and manage the water-energy-food nexus to improve governmental decision-making processes across countries[11]. Specifically, MuSIASEM is at the present considered as an important framework of this project. Besides that, the methodology has been taught in different countries to researchers, scholars and decision makers through its platforms known as LIPHE4. A case of this is the special advisory for the National Plan for Good Living from Ecuador's government.[12]

'Questions are necessarily prior to answers, and no answers are conceivable that are not answers to questions. A "purely factual" study—observation of a segment of social reality with no preconceptions—is not possible; it could only lead to a chaotic accumulation of meaningless impressions. Even the savage has his selective preconceptions by which he can organize, interpret, and give meaning to his experiences.'

Myrdal, 1968, p. 24 cited in Meadows, 1980, p. 23

MuSIASEM as a narrative for sustainability

MuSIASEM possess a high value as an accounting framework for energy issues, it provides the possibility to evaluate from a bio-economic perspective the energy use in a society with special focus on the analysis management of the main categories considered in the approach: gross energy requirement, energy carriers, net energy supply. Those bring the basis to assess the quality of alternative energy sources and evaluate the actual energy requirement of a society. It fails to explain how the energy processes take part under this approach in detail, it was developed as an accounting system and the grammars it provides improve the understanding of energy accounting categories, but are insufficient to bring enough information that could be replicated in modeling exercises by other methodologies using it as a narrative, such as SD.

MuSIASEM develops indicators that give a snapshot on how the system is working in a certain moment of time. As they are just indicators, they do not provide any explanatory elaboration about

[10] Nexus The Water, Energy and Food security Resource Platform, Electronic source http://www.water-energy-food.org/en/whats_the_nexus/background.html

[11] The Energy-Food-Water nexus A Water-Energy-Food Nexus Approach to Inform Policy-Making, Food and Agriculture Organization by United Nations, Electronic source: http://www.fao.org/energy/81320/en/

[12] The Nexus between Energy, Food, Land Use, and Water: Application of a Multi-Scale Integrated Approach, electronic sources: http://www.liphe4.org/en/home, http://www.nexus-assessment.info

the internal organization of the society that gives birth to them. In terms of sustainability, this explanatory component is crucial to understand what is going on in the system, and which are the key points to sustain or determine the unviability of the energy use patterns. The development of benchmarks to assess the functioning of the system and compare with other metabolic systems, as MuSIASEM proposes, help to develop hypothesis on what should be happening in the society but it does not provide a way of taking that research further on.

Human activity is a biophysical factor considered in the evaluation of the societal metabolism and it is one of the most relevant in MuSIASEM. Its consideration opens the door to a new set of variables to analyze because of its consideration of human time in the functioning of a society. It represents a qualitative advancement for sustainability assessments using the biophysical component of human activity in an integrated valuation of energy resources. The interpretation of *human activity* as a fund could be misleading for a sustainability analysis. *Human activity* is an extensive variable that does not possess any accumulation processes; it is calculated by the Population size and time. It cannot be accumulated is just allocated in different activities. The implication of this categorization for sustainability analysis is important because HA available is the result of the dynamics driving changes in the composition and size of populations. On the other hand, the allocation of *Human act*ivity in the society depends on the internal constrains and structures of the socioeconomic system. Also, these represent key points where the focus of the sustainability analysis should be: the population composition changes and the internal socioeconomic dynamics. MuSIASEM represents a qualitative improvement on the narrative level for current governance issues dealing with sustainability.

The division of societal levels makes manageable the information derived of each, in the quest for a comprehensive analysis of complex systems that human societies are. In addition, the assessment of what is called "societal metabolism" given by the energy use units and human activity time represents an innovation on sustainability analysis for the integral consideration of economic and biophysical elements.

Yet, as not conclusive and open to external disciplines' narrative scrutiny, as its authors state, the findings gotten from the SD methodology could support the improvement of narratives on sustainability, where the acknowledgment of the dynamic change of organic and non-organic funds supporting all human processes can only be addressed by the right categorization of funds and flows. Flows that provoke the change of funds over time and that are driven by specific dynamics resulting from the internal organization of human societies.

If we attach to a meaningful definition of sustainability, the coherence of the human processes with the external constraints could be applied in designing more *viable* dynamics at different societal levels that regulate the supply and consumption flows, finding opportunities to close loops. Or establishing controls, which can be used to substantiate the desirability condition mentioned by the framework. MuSIASEM's idea of sustainability it is based on the maintenance and reproduction of the fund elements in the metabolic process of society during the period of analysis, but it does not say how. SD could be a useful tool to open the "black box" in order to look for the viability principle that MuSIASEM addressed.

Selection of the time horizon to analyze changes in the dynamic energy budget presents challenges to be integrated in a model on the human metabolism because the internal organization of society is important to be analyzed in shorter time scales. While energy shifts in human society should be analyzed in longer periods of time, but by adopting a higher time scale, the observation of the internal organization of society might be lost, moreover, changes in the structure of that internal organization might have occurred, making the societal analysis meaningless.

Changes in the energy supply for a society derived from any drastic change in primary energy sources, in the context of high dependency on non-renewables energy, will provoke mismatches in the society that might result in an internal reorganization. Society will have to adapt, in this case, the external constrains that are part of the system structure will push changes in the internal dynamics and processes. Nevertheless, the way the society will react cannot be known with certainty. SD can assess until certain points the consequences of the reduction of energy supply, but it is not able to explain how agents or system micro organizations will react to this. Hypothesis on these changes can be plotted in an SD model in order to generate scenarios. In order to make simulation research of possible scenarios considering individual agents behavior towards societal adaptability assessment would require other simulation methodologies for example, agent based modeling (ABM).

Use of the framework and replicability of the application cases

In order properly apply of the methodology to new study cases, and test the replicability of the results from studies already developed, it is important that MuSIASEM addresses the gaps existing in its literature regarding:

1) The innovation on the energy accounting perspective the framework holds, requires clear and complete information on the energy transformation processes along the resources life-time. Yet, the remittances to specific authors or fields on ways of accounting the production process or the EROI in the scheme the methodology proposes, can be helpful to extend the application of this methodology.

2) The correct reinterpretation of the fund and flows categories along the framework, in order to maintain the sustainability assessment through the viability, feasibility and desirability checks.

3) Clarity in the total existing societal levels of MuSIASEM; some publications refer to 3, 4 or 5 levels, applying the analysis for different purposes in each. A detailed explanation on the implications of each boundary selection and examples of the forms of accounting that can be done, would be very helpful in eliminating confusion, and could extend the applications to different kinds of assessments.

Proposals

1) Develop a specialized document that contains the concepts, the total scales or societal levels considered in MuSIASEM and the reasons and usefulness of their boundaries selection, metabolism indicators and calculation procedures, distinctions between funds and flows in main variables for the nexus assessment, detailing the guidelines of the methodology tools (multipurpose grammar, multilevel matrix) that have been used in applications cases already developed, examples of other kind of analysis that could be done with complete equations and values of the results calculations.

The narrative of this document attached to policy-making language could increase the comprehension of the readers and the framework's applicability. All former ideas could be very useful for a SD model development.

2) Develop a society prototype on the simplest ways the societal metabolism in that society could develop in order to provide explanatory capacity. This prototype can be extended and adapted according to the purpose and nature of further studies using the framework, but in the first place, it could provide an explanatory capacity of the framework that is hard to achieve by reading the literature, using the matrices and tools for the analysis or looking to different application cases because of the diversity of the applications.

Within the framework we have seen how for instance some visualization tools analyze level N-3 of society. These are dealing with hypothetical societies of 100 inhabitants. The prototype of the societal metabolism proposed here would have to include the dynamic energy budget simplest assumptions and its relation with the human activity component developed in the framework. Until now, the literature existing on the framework is mainly based on either application cases, epistemological challenges of the new energy accounting or working papers where sustainability concerns, energy accounting challenges and application cases are explained but with important gaps to understand how those cases were assessed and until which point it relied completely on the framework. It is still missing a practical document on application of the methodology issues.

Agenda for further research

1) Try to open the "black box" that will make it possible to clarify the viability of the "societal metabolism" by modeling the internal socioeconomic structure that drives the requirement of energy in the society.

2) Explore equilibrium states derived from the changes on different levels.

3) Performing SD modeling exercises with the indicators provided by MuSIASEM as milestones in the modeling process and get support of the disciplines that present coherent knowledge within the MuSIASEM narrative.

4) Addressing the gaps of information regarding the Dynamic Energy budget in order to get a complete dynamic model on the societal metabolism changes.

It is important to clarify that simulation research can be considered a tool not to predict but rather to understand the dynamics of where human society is embedded for policy recommendation purposes and possible redesign of the societal energy use patterns.

Glossary:

Total primary energy supply: The total primary energy supply (TPES) is the sum of all energy resources worldwide, like coal, oil, gas, nuclear, and hydro. These resources are converted into gasoline, natural gas, electricity, and many other energy carriers. Is the sum of production and imports subtracting exports and storage changes. [13]

Final energy consumption: Final energy consumption of households is driven by disposable income (a function of economic growth), population, the number of households and size of the dwellings. The indicator measures to what extent there is a decoupling between final energy consumption in various sectors and these drivers. A decoupling of final energy consumption from economic growth indicates a reduction in environmental pressures from energy production and consumption due to avoided supply of energy. Energy supplied to the final consumer for all energy uses. It is calculated as the sum of final energy consumption of all sectors. These are disaggregated to cover industry, transport, households, and services and agriculture. Total final energy intensity is defined as total final energy consumption (consumption of transformed energy such as electricity, publicly supplied heat, refined oil products, coke, etc, and the direct use of primary fuels such as gas or renewables, e.g. solar heat or biomass) divided by gross domestic product (GDP) at constant 2000 prices.[14]

Non-Energy Use: covers those fuels that are used as raw materials in the different sectors and are not consumed as a fuel or transformed into another fuel. Non-energy use is shown separately in final consumption under the heading non-energy use. Note that for biomass commodities, only the amounts specifically used for energy purposes (a small part of the total) are included in the energy statistics. Therefore, the non-energy use of biomass is not taken into consideration and the quantities are null by definition.[15]

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[13] OECD Factbook 2013: Economic, Environmental and Social Statistics". 2013. Retrieved 12 April 2014.
[14] Ibid.
[15] Ibidem.

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Appendix

Table 1. Case selection criteria

Criteria (10-30)	Farming System in Guatemala	Catalonia's energy metabolism	Argentina
Quantity of info in the paper	Sufficient (2)	Need for research (3)	Very sufficient (1)
Simulation results	Predicative loops format, no series time (3)	Variety of comparison possibilities, time series and pie graphs included (1)	Very sufficient (1)
Authors knowledge of the framework	Students (3)	Framework authors (1)	Part of the research team (2)
Accessibility of authors	(3) Unknown	(1) Direct contact	(1) Accessible to direct contact
Clear conclusions and evaluation method	Very Sufficient (1)	Sufficient (2)	Very sufficient (1)
Class of paper	Working paper CEPAL (2)	Academic paper (1)	Academic paper (1)
Size of the model	(1) One sector model	(4) Several sector model	(1) Two sector model
Sources to keep researching on the topic	(3) Not available	(1) Available	(2) Unknown yet
Feedbacks elicited from the application case	(2) Sufficient	(1) Very sufficient	(2) Sufficient
Policy testing possibilities	(3) Very narrow	(1) Very diverse	(2) Narrow
	18	15	14

Argentina Case Equations:

Added_value_per_working_hour_of_sector_i =
UNITS: Argentinian Pesos/hours (ArgentinianPesos/hours)
annual_work_in_AG_pp = 48*weekly_hours_in_AG_per_person
UNITS: hours/people (hours/people)
annual_work_in_PS_pp = 48*weekly_hours_in_PS_per_person
UNITS: hours/people (hours/people)
annual_work_in_SG_pp = 48*weekly_hours_in_SG_per_person
UNITS: hours/people (hours/people)
average_GVA =
constant_prices_of_1990 =
Energy_efficiency_of_production = Labour_productivity/MR_paid_work
UNITS: Argentinian Pesos/joules (ArgentinianPesos/joules)
DOCUMENT: ELPi/EMR GDPi/ETi: Energy Efficiency of Production: Added!value generated per unit of energy consumption in sector i,!measured in U.S. dollars/Joules.
energy_for_consumption_of_economic_sectors = non_energy__use_energy_sector+ total_final_consumption_primary_sources+energy_sector__own_use
UNITS: joules (j)
Energy_intensity = primary_energy__consumption/GDP
UNITS: joules/ArgentinianPesos
energy_sector__own_use =
UNITS: hours per week (hoursperweek)
energy_use_by_economic_sectors =
Energy_use_HH = final_energy_available_for_consumption*fraction_of_energy_use_in_HH
UNITS: joules (j)
Energy_use_PW =
energy_use_by_economic_sectors*final_energy_available_for_consumption
UNITS: joules (j)
final_energy_available_for_consumption = energy_for_consumption_of_economic_sectors-(transformation_losses*energy_for_consumption_of_economic_sectors)
UNITS: joules (j)
fraction_of_energy_use_in_HH = 0.25
UNITS: Unitless
GDP = GRAPH(TIME)
(1990, 135555), (1991, 148823), (1992, 162626), (1993, 172627), (1994, 182821), (1995, 182857), (1996, 192463), (1997, 207256), (1998, 215373), (1999, 208019), (2000, 205755), (2001, 196617), (2002, 176934), (2003, 191605), (2004, 206514), (2005, 223060), (2006, 240199), (2007, 246684)
UNITS: Argentinian Pesos (ARP)
HA_HH = HH*weeks_per_year*HH
UNITS: hours (hr)
DOCUMENT: Human Activity households: Human time in the household!sector in one year, measured in hours!!Total human activity for the activity i; W: working!weeks per year; POi: population in the activity i; HsSi: weekly hours!of work in the activity i.
HA_PW = PW*(annual_work_in_PS_pp+annual_work_in_AG_pp+annual_work_in_SG_pp)
UNITS: hours (hr)
DOCUMENT: Human Activity paid work: Human time in the productive!sector in one year,

measured in hours (h).!!Total human activity for the activity i; W: working!weeks per year; POi: population in the activity i; HsSi: weekly hours!of work in the activity i.
HH = Population*HH_fraction
UNITS: Unitless
HH_energy_used__per_working_hour =
UNITS: joules/hours
Labour_productivity = average_GVA/HA_PW
UNITS: Argentinian Pesos/hours (ArgentinianPesos/hours)
DOCUMENT: Added value per hour of working time in sector i
losses =
UNITS: Unitless
MR_HH = Energy_use_HH/HA_HH
MR_paid_work = Energy_use_PW/HA_PW
UNITS: joules/hours
non_energy__use_energy_sector = energy_sector__own_use*.2
UNITS: joules (j)
Population = GRAPH()
(1990, 3.3e+07), (1991, 3.4e+07), (1992, 3.4e+07), (1993, 3.5e+07), (1994, 3.5e+07), (1995, 3.5e+ 07), (1996, 3.6e+07), (1997, 3.6e+07), (1998, 3.7e+07), (2000, 3.7e+07), (2001, 3.7e+07), (2002, 3.8e+07), (2003, 3.8e+07), (2004, 3.9e+07), (2005, 3.9e+07), (2006, 3.9e+07), (2007, 4e+07)
UNITS: people (person)
primary_energy__consumption = total_final_consumption_primary_sources+ energy_sector__own_use+losses
UNITS: joules (j)
PW = Population*PW_fraction
UNITS: people (person)
PW_energy_consumption_per_working_hour =
UNITS: joules/hours
PW_fraction = 0.75
UNITS: Unitless
THA = HA_HH+HA_PW
UNITS: hours (hr)
DOCUMENT: Total Human Activity: Total human time a society has available for conducting different activities (endosomatic and exosomatic consumption), measured in hours (h). (Population times 8760 h)
total_final_consumption_primary_sources =
UNITS: joules (j)
transformation_losses =
UNITS: Unitless
weekly_hours_in_AG_per_person = 48.5
UNITS: hours per week (hoursperweek)
DOCUMENT: 48.5
weekly_hours_in_PS_per_person = 43.27
UNITS: hours per week (hoursperweek)
weekly_hours_in_SG_per_person = 38
UNITS: hours per week (hoursperweek)

Human Activity Model Equations

PEOPLE(t) = PEOPLE(t - dt) + (net_migration_1 + births_1 - deaths_1) * dt
INIT PEOPLE = 32642000
UNITS: people (person)
INFLOWS:
net_migration_1 = net_migration
UNITS: person/yr
births_1 = births
UNITS: person/yr
OUTFLOWS:
deaths_1 = deaths
UNITS: person/yr
Agriculture = HA_Paid_worl*.2
UNITS: hours/year
births = GRAPH(TIME)
(1990, 678644), (1991, 694776), (1992, 678761), (1993, 667518), (1994, 673787), (1995, 658735), (1996, 675437), (1997, 692357), (1998, 683301), (1999, 686748), (2000, 701878), (2001, 683495), (2002, 694684), (2003, 697952), (2004, 736261), (2005, 721220), (2006, 696451), (2007, 700792)
deaths = GRAPH(TIME)
(1990, 398551), (1991, 449275), (1992, 528986), (1993, 550725), (1994, 586957), (1995, 637681), (1996, 644928), (1997, 666667), (1998, 688406), (1999, 695652), (2000, 673913), (2001, 710145), (2002, 760870), (2003, 760870), (2004, 760870), (2005, 753623), (2006, 753623), (2007, 797101)
Educational_act = HA_house_holds*.3
UNITS: hours/year
Energy_and_Mining = 0.2*HA_Paid_worl
UNITS: hours/year
GAP_PW = HA_Paid_worl-labor_demanded
UNITS: hours/year
HA_house_holds = PEOPLE*hours__per_year-HA_Paid_worl
UNITS: hours/year
HA_Paid_worl = Working__Population'*PEOPLE*working_hours_per_week*
Working_weeks_per_year
UNITS: hours/year
hours__per_year = 8 736
UNITS: hours/year

Industry = .3*HA_Paid_worl
UNITS: hours/year
labor_demanded = 60107560000
UNITS: hours/year
Leisure_and__recreation_time = HA_house_holds*.4
UNITS: hours/year
net_migration = GRAPH(TIME)
(1990, 50870), (1992, 53913), (1995, 57391), (1997, 57391), (2000, 55217), (2002, 60435), (2005, 63043), (2007, 63043)

non_working__hours_per_week = 168-working_hours_per_week
UNITS: hours/weeks
Non_working__population = 0.35
UNITS: 1/people
non_working__weeks_per_year = 52-Working_weeks_per_year
UNITS: weeks/years
Services_and_Government = .5*HA_Paid_worl
UNITS: hours/year
Sleeping_time = 0.3*HA_house_holds
UNITS: hours/year
THA = HA_house_holds+HA_Paid_worl
UNITS: hours/year
working_hours_per_week = 40
UNITS: hours/weeks
Working_weeks_per_year = 48
UNITS: weeks/years
Working__Population' = 0.65
UNITS: 1/people

Dynamic Energy Budget equations

Capital(t) = Capital(t - dt) + (net_change__in_capital) * dt
INIT Capital = 50000000
UNITS: Argentinian Pesos (ARP)
INFLOWS:
net_change__in_capital = Capital*average__capital_increasecapital_
needed_per__production_plant_per_year*Power__capacity
UNITS: arp/yr
Land(t) = Land(t - dt) + (net_land_change) * dt
INIT Land = 30000
UNITS: hectares (ha)
INFLOWS:
net_land_change = -average_land__use_per_year
UNITS: hectares/yr
Power__capacity(t) = Power__capacity(t - dt) + (increase__in_pc - yearly__utilization) * dt
INIT Power__capacity = 20
UNITS: factories (factory)
INFLOWS:
increase__in_pc = Power__capacity+(Power__capacity*
capacity_fraction_increase)
UNITS: factory/yr
OUTFLOWS:
yearly__utilization = Power__capacity-(Power__capacity*fraction__utilization)
UNITS: factory/yr
Proven__PES(t) = Proven__PES(t - dt) + (PES__imports - Production - Exports_PES) * dt
INIT Proven__PES = 12000000
UNITS: tons
INFLOWS:
PES__imports = average__anual__PES__requirement
UNITS: tons/yr
OUTFLOWS:
Production = (Proven__PES*extraction_rate_per_year)-Proven__PES*
extr__losses*extraction_rate_per_year)*conversion__fraction)/
Power__capacity*average_production__per_plant_per_year+DELAY3()
UNITS: tons/yr
Exports_PES = (PES_ex_rate*Proven__PES)+(PES_ex_rate*Proven__PES*
extraction__losses)
UNITS: tons/yr
Technology(t) = Technology(t - dt) + (net_change__in_tech) * dt
INIT Technology = 26
UNITS: units (unit)
INFLOWS:
net_change__in_tech = Technology*change_in_tech_per_year
UNITS: unit/yr
Water(t) = Water(t - dt) + (change_in__water) * dt
INIT Water = 9000000000

UNITS: cubic meters (m^3)
INFLOWS:
change_in__water = (average_water_increase__per_year*Water)-(rest_of_water__consumption+water_needed_per_EM_sector_per_year)
UNITS: m^3/yr
UNATTACHED:
ET = Production-(Production*losses_dist)+imports_of_Energy_for_consumption-(exports*Production)
UNATTACHED:
Imports =
available_capital__for_production = 1
average_labour_per_unit__of_production = 2
UNITS: hours/tons
average_land__use_per_year = 10000000+(Land_usage_per_unit_of_conversion*Production)
UNITS: hectares/yr
average_production__per_plant_per_year = 90000
UNITS: tons/yr
average_water_increase__per_year = 0.1
UNITS: per year (1/yr)
average__anual__PES__requirement = 100000
UNITS: per year (1/yr)
average__capital_increase = 0.3
UNITS: per year (1/yr)
capacity_fraction_increase = 0.011
UNITS: per year (1/yr)
capital_needed_per__production_plant_per_year = 1
UNITS: ArgentinianPesos/factories
change_in_tech_per_year = 0.0001
UNITS: per year (1/yr)
conversion_fraction__mechanical_to_therma = 0.3
UNITS: Unitless
conversion__fraction = technical__conversion___efficiency*1⍰
UNITS: tons/joules
Energy_and__mining_HA = 0
UNITS: hours/year
EROI__enery_return__on_investment = TET*investment_fraction
exports =
extraction_rate_per_year = 0.001
UNITS: per year (1/yr)
extraction__losses = 0.26
UNITS: per year (1/yr)
extr__losses = 0.3
UNITS: per year (1/yr)
fraction__utilization = 0.011
UNITS: per year (1/yr)
gross_energy__requirement = EROI__enery_return__on_investment+

imports_of_Energy_for_consumption +(average__anual__PES__requirement*
thermal_energy__equivalence)
imports_for__consumption =
imports_for__production =
UNITS: per year (1/yr)
imports_of_Energy_for_consumption = imports_for__consumption*Imports
imports_of_energy_for_production = Imports*imports_for__production
UNITS: tons/yr
import_rate =
UNITS: tons/yr
labour_gap = Labour
Labour_required_by_EM = Production*average_labour_per_unit__of_production
UNITS: hours/year
Land_usage_per_unit_of_conversion = 1e-09
UNITS: hectares/tons
losses_dist =
PES_ex_rate = 0.001
UNITS: per year (1/yr)
Potential__supply = gross_energy__requirement/ET
UNITS: joules (j)
rest_of_water__consumption = 1700000
UNITS: per year (1/yr)
SEH = ET/EROI__enery_return__on_investment
DOCUMENT: According to the book, page 74, this ratio determines the quiality of PES ???
technical__conversion___efficiency = GRAPH(Technology)
(0.00, 0.141), (10.0, 0.149), (20.0, 0.185), (30.0, 0.225), (40.0, 0.29), (50.0, 0.348),
(60.0, 0.507), (70.0, 0.743), (80.0, 0.902), (90.0, 0.975), (100, 0.996)
thermal_energy__equivalence = 42
UNITS: joules/tons (joules/tons)
water_needed_per_EM_sector_per_year = Production*
water_usage_per_unit_for_conversion
UNITS: cubic meters (m^3)
water_usage_per_unit_for_conversion = 120
UNITS: cubicmeters/tons