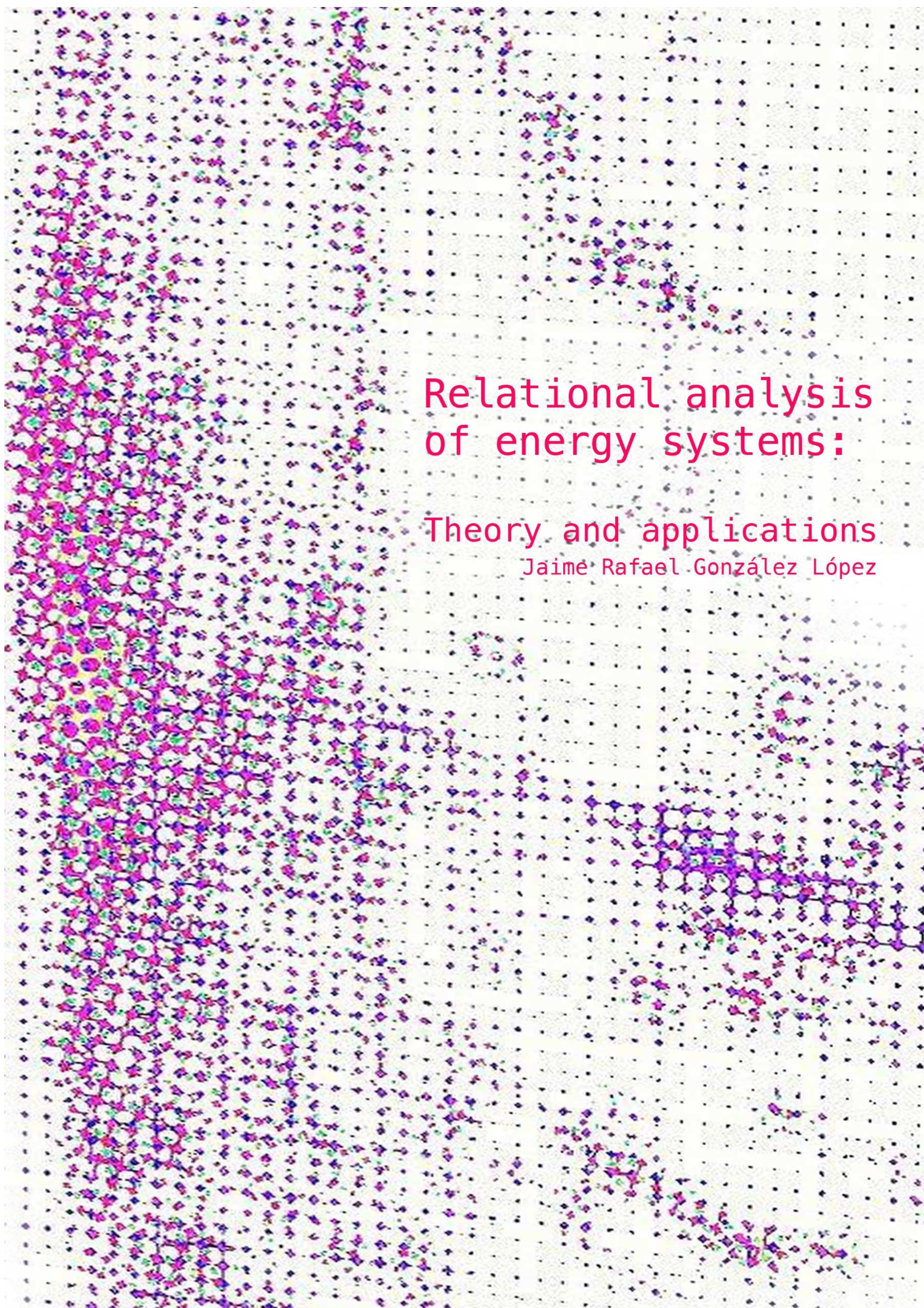
Relational analysis of energy systems:
Theory and applications

Jaime Rafael González López



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Preface

I remember when I read the phrase from Paulo Freire *"o Mundo não e, o Mundo ta sendo"*. Now, I realize that perhaps in words of Prigogine, this is what he meant with becoming systems. This way of thinking opened my mind and I realized that we are a world under construction, and that is false that is a closed system in which everything is already thought/spoken. On the other side, I was inspired by the TED talk *Want to innovate? Become a "now-ist"* by Joi Ito, when he made research for the problem that was faced in the tsunami that affected Japan, where he and many researchers made strong efforts to contribute for the solution of this problem. I tried to apply this in the development of my thesis as a scientist and as a human being, so this thesis is based in current situations that are occurring in Mexico in specific in the Energy Reform context, and now that I'm living in Europe, I can say that here as well in the energy field. Many discourses of presidents incorporate the energy panorama in their agenda, misleading or sometimes missing a more integral way to see the energy systems.

What I have realized is that many times when energetic systems are analyzed we are losing the meaning or the information of why the energy is produced and the changes that must be taken to manage these systems, and that just an engineering point of view can't solve the needs of the problems that are faced today. Or in words of Einstein, we cannot solve problems thinking the same way we have created them.

The new thing I am contributing mainly is the incorporation of relational analysis in the MuSIASEM approach. With this, I answered many unknowns that were addressed when we analyze energy systems. We thought that we must address that there're more things to talk than efficiency (some of the most popular energy analysis tools were developed under these circumstances). That we need to address the relation of systems with nature, other socioeconomic systems and with themselves.

I thought that many of the analyses were in some sort autistic, missing the wholeness and by this the usefulness of the different energy systems analyzed.

I think many of the current problems is how systems are analyzed isolated and many decision-making scenarios are based on this type of analysis. I don't know if this is the reason why our understanding is not so good or if we are in a moment where this analysis is not enough to address the complexity.

There are many questions that I realize, for example, if we reduce the analysis in one side using money, we are losing all the information on the natural cost of managing one resource.

On the other hand, after analyzing many systems from a biophysical perspective I realized that they are not linked with the value of production. There's the vision that the market can control this, but I think it is not the same biophysical price or social in some way to produce the same thing in different places.

In the end, this is not a recipe, but I hope it can help to change the way we think about systems.

Abstract

This thesis presents a novel framework for the biophysical energetic analysis of social-ecological systems based on complexity theory. Through the implementation of MuSIASEM and Relational Analysis, it generates information useful for policy discussion in a complex world where understanding sustainability is necessary. Also, it is useful for contesting agendas at integrating non-equivalent information. With the integration of the functional and structural perspective of complex systems, questions like where, how, why and what are addressed.

This framework is demonstrated with some examples mainly in the Mexican Energy Reform context. You can find that al examples cover a broad diversity of energetic systems: biomass, oil and gas, electricity, and it also is argued why this framework is necessary compared to the most popular methodologies in the contemporary era. Reducing sustainability into some ratios is avoided. This thesis embraces complexity by analyzing the non-linear relations among the different social-ecological systems with the environment and within themselves. How these relations affect different outcomes and by these the anticipation which is necessary to understand when making plans for the systems under dispute.

You can find in this thesis theoretical, methodological and contemporary applications of this framework.

Structure of the thesis

The structure of the thesis may follow the line of the appearance of the different energy sources. From biomass to fossil fuels ending with "renewable" sources of electricity production.

Introduction

I introduce the reader to different sections. I explain in my own words in a general way why it is important the MuSIASEM analysis and its integration with the Relational Analysis. In the next sections, you can find references to all the works and their own introduction.

First Chapter: Charcoal metabolism (paper published)

It presents an application of the Relational Analysis and MuSIASEM to the metabolism of a village. This village is in the transition from biomass to fossil fuel, and thus implies many adjustments over functional and structural elements in the village, due to the change from subsistence into a market-based village. Within the chosen analytical framework this change can be related to the change of type of fuel and changes in social practices within the economy.

Second Chapter: Oil and gas metabolism (paper published)

It presents an application of the Relational Analysis and MuSIASEM to the oil and gas sector of Mexico; the analysis is used to comment on the current Energy Reform in Mexico. This chapter brings a biophysical analysis of the oil & gas sector of Mexico. Looking at the current pattern of oil and gas production in Mexico it discusses whether Mexico should remain with the same pattern or change it. It also shows the importance of complementing the economic analysis with other types of analysis dealing with issues such as energy sovereignty, environmental impact and geographic location of economic activities. In short, it shows the importance of complementing reductionist analysis when planning.

Third chapter: Electricity metabolism (paper accepted for an international conference)

It presents an application of the Relational Analysis and MuSIASEM to the electricity production in Mexico. The analysis of the relations between structural and functional elements allow studying the nexus between land, energy, and emissions. In particular, it elucidates the spatial constraints that can be associated with the expansion of alternative sources of electricity. In the past, we emancipated from the need of using a lot of land for energy purposes by using fossil fuels. But how strong is this emancipation when relying on intermittent electricity (wind and PV)? To answer this question, we have to address the increasing demand for importation of natural gas as a back-up of the intermittent sources of electricity, and the potential rebound effect of this solution, if the pattern of consumption remains the same.

Fourth Chapter: Going beyond "efficiency ratios" (paper accepted for an international conference)

I demonstrate how the functional perspective can be used to introduce a novel approach to energy system analysis This application shows the weakness of assessments based on ratios (EROEI for example) if we want to address the complexity associated with sustainability. Radical simplifications of indicators of energy performance (simplistic definitions of energy) can be useful for those interested in "technofixes" but not for understanding the functioning of the system. For this reason, a systemic analysis of structural and functional relations should be incorporated in the energy analysis if we want to make it useful for the understanding of the interaction of socioecological systems.

Fifth chapter: Discussion and Conclusion

The combination of relational analysis and MuSIASEM allows answering questions necessary for energetic analysis and that are essential for policy discussion. By adopting system thinking becomes possible to incorporate in the analysis key aspects of energy analysis that in general are overlooked in conventional analysis: the different quality of the energy forms accounted in energy flows; the difference between stock-flow and fund-flows; the key role of assessments of power capacity. In turn, considering these aspects allow addressing in an integrated way the “what”, “why”, “where” and “how” questions while embracing complexity.

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Introduction

This section is written more generally (In my words). In the following sections you can find more detailed references to the information provided in the thesis, and also in the introduction of each chapter. In this way, I think that the introduction fulfills its objective of introducing the reader in more complex and developed parts.

1. What do I think MuSIASEM and Relational Analysis are?

I see MuSIASEM as a way of conceptualizing how the metabolic pattern of the different components of a society can be analyzed and characterized at different levels and across different dimensions of analysis. It provides an analytical framework for the characterization of: (i) the functioning of the constituent components needed by societal-ecological systems for reproducing themselves; (ii) the interaction of societal-ecosystems with their embedding ecosystems; and (iii) the interaction of societal-ecological system among themselves. This analytical framework: (i) combines different metrics referring to different scales and dimensions; (ii) incorporates the distinction proposed by Georgescu Roegen between stocks, flows, and funds in the representation of the metabolic pattern; (iii) describes the transformation of the quality of the funds, stocks, flows necessary to reproduce, maintain and transform society.

I see relational analysis as the definition of an expected set of relations over structural and functional elements associated with the expression of the metabolic patterns of different social-ecological systems. The various sets of expected relations can be described inside the elements of social-ecological systems, when considering their interaction with nature, and when considering their interaction with other social-ecological systems. The definition of an expected set of relations entails: (i) the integration of non-equivalent definitions of the same system: structure and function;

and (ii) the emergent pattern determined by the interaction of processes taking place simultaneously across different levels and scales of analysis.

Additional special characteristics of these systems are: (i) they are anticipatory – as suggested by Robert Rosen one of the fathers of relational analysis; (ii) they are becoming systems – as suggested by Ilya Prigogine one of the fathers of non-equilibrium thermodynamics; (iii) they are adaptive, meaning that they "interpret and learn" from their interaction with the external world – as suggested in biosemiotics.

2. Why should relational analysis and MuSIASEM be combined?

The combination of relational analysis and MuSIASEM makes it possible to integrate: (i) the semantic step – i.e. the identification of the WHY/WHAT in the perception - why are we doing the analysis, how to identify the constituent components in terms of expected relations (relational analysis); and (ii) the formal step – i.e. the identification of the HOW/WHAT in the representations – how are we generating a quantitative analysis of the relations over the activity of functional and structural elements. In this way, it becomes possible to represent the set of transformations of funds, flows and stocks of the system (in a DIAGNOSTIC mode) and then use the expected set of relations to run possible scenarios of changes of the flows across the metabolic patterns (in an ANTICIPATION mode) (Giampietro, 2018). An example of the representation of the different processes necessary to produce goods and services and the various activities required to guarantee the maintenance, repair, and changes of each of its constituent components obtained in this way, is illustrated in Figure 0-1.

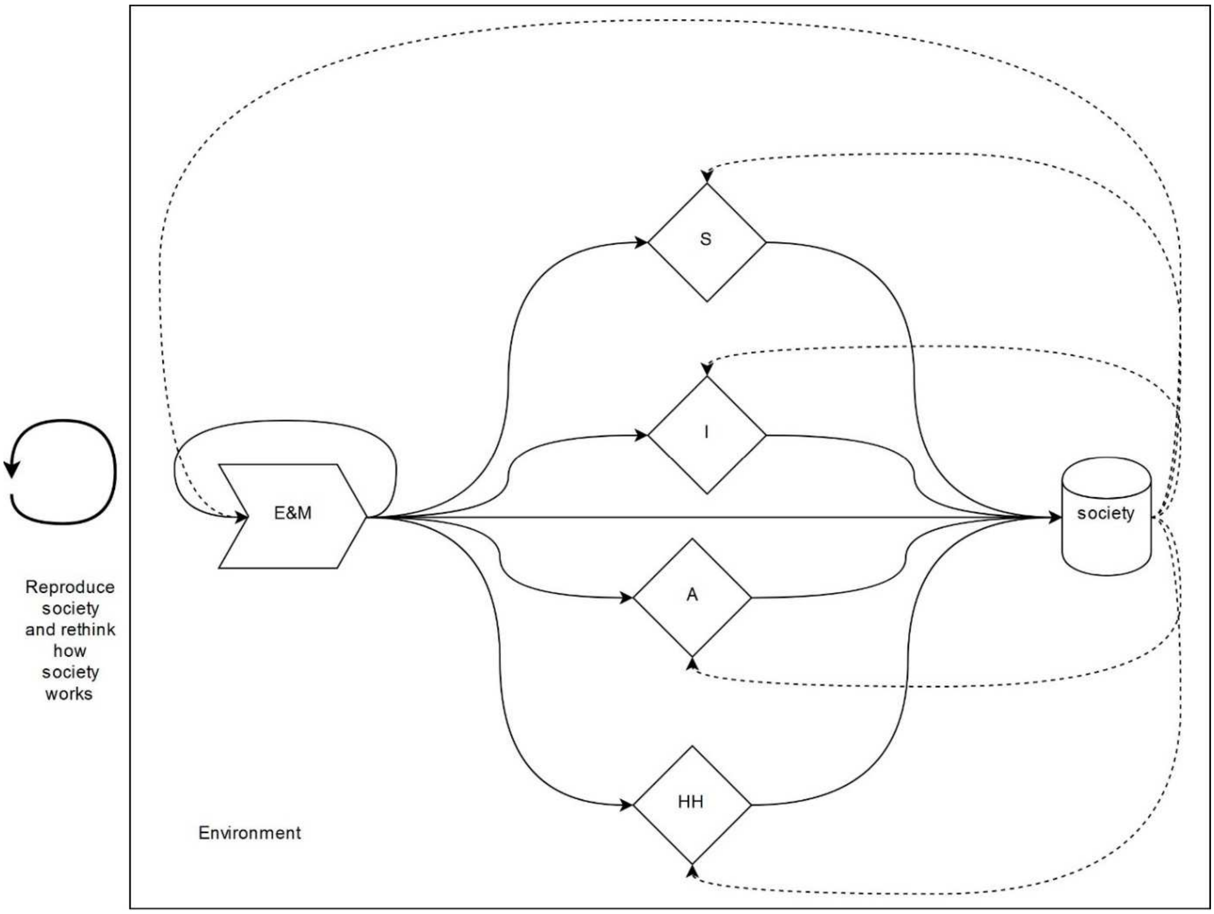

Figure 0-1 Reproduction and self-maintenance of society observed from the energetic point of view.

I = Industrial sector, A=Agricultural sector, HH= Household sector, S=Service sector, E&M=Energy, and mining.

Another thing that is important to talk about is the usefulness of the different energy produced. In this thesis, you will find a functional part of all energy production. I think this is missing in many of the analysis if not in all. And it has to do with the usefulness of the different energetic and non-energetic products in the interaction of production and demand.

Objectives

-Develop a non-reductionist analytical framework for energetic analysis

-Incorporate a spatial approach into energy analysis

-Integrate available information across dimensions and scales to obtain a holistic vision

-Generate anticipatory outcomes useful for policy discussion.

Objectives

Methodology[1]

MuSIASEM

The MuSIASEM accounting framework organizes quantitative information about different dimensions of analysis—i.e., social, economic, technical, biophysical, ecological—and different hierarchical scales of analysis referring to both socio-economic narratives and an ecological narrative (Madrid-López and Giampietro, 2015). In this way, the information generated can be used to check three dimensions of sustainability:

1. Feasibility—This dimension sees the system (society) as a black-box interacting with its context. Feasibility thus refers to the compatibility of the metabolic system with processes beyond human control, that is, external constraints imposed by the availability of natural resources and ecosystem services. This dimension involves (i) checking whether the metabolism of the system (seen as a black box) is compatible with the boundary conditions, and (ii) checking the level of openness of the system in terms of trade with other social-ecological systems (the extent of externalization to or dependence on other social-ecological systems);

2. Viability—This dimension looks at the workings inside the black-box to check the interactions among its parts. Viability thus addresses the compatibility of the system in relation to processes under human control (e.g., economic viability, technical viability) by checking whether the interaction of the parts inside the black box is compatible with available technology and know-how;

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[1] This chapter builds on the published papers:
González-López, R., & Giampietro, M. (2017). Multi-Scale Integrated Analysis of Charcoal Production in Complex Social-Ecological Systems. Frontiers in Environmental Science, 5. https://doi.org/10.3389/fenvs.2017.00054
González-López, R., & Giampietro, M. (2018). Relational Analysis of the oil and gas sector of Mexico: Implications for Mexico's Energy Reform. Energy. https://doi.org/10.1016/j.energy.2018.04.134

3. Desirability—This dimension checks whether the characteristics of the metabolic pattern are acceptable to those living inside the system (the desirability of the metabolic pattern directly affects the stability of the social fabric).

MuSIASEM basically consists of a relational analysis of the functional and structural elements of a social-ecological system that together determine its metabolic pattern of resources. The concept of metabolism is commonly associated with the human body to represent the complex processes converting food into the energy and building blocks required to maintain its structure and functions. However, the concept of metabolism can also be and indeed has been applied to social-ecological systems (Ostwald, 1907, 1911; Lotka, 1922, 1956; Soddy, 1926; Zipf, 1941; White, 1943; Cottrell, 1955). Complex societies exhibit a mechanism of reproduction and maintenance like that of the human body. They extract and use a mix of energy and material inputs from their environment to express the functions required for preserving their identity. Along these premises, a new scientific field has emerged that is based on the study of "societal (or social) metabolism" (Wolman, 1965; Martinez-Alier, 1987; Fischer-Kowalski and Hüttler, 1998; Daniels, 2002; Swyngedouw, 2006; Giampietro et al., 2009; Broto et al., 2012; Giampietro, 2014). Metabolic pattern refers to the expected profile of inputs (taken from the environment) and outputs (discharged into the environment) associated to the set of functions required to reproduce the identity of a given social-ecological system (Giampietro et al., 2011). The concept of metabolic pattern neatly shows that the nexus between water, energy, and food is determined by forced relations among the structural and functional elements of a complex system. The term "relational analysis" (Rosen, 1958, 1985; Louie, 2009, 2013) indicates the existence of expected patterns of relations over the elements of metabolic networks that are capable of self-reproduction and self-maintenance. It implies a distinction between: (i) inputs and outputs remaining inside the self-organizing system; and (ii) inputs and outputs exchanged with the context. MuSIASEM also borrows from hierarchy theory

(Koestler, 1968; Whyte et al., 1969; Allen and Starr, 1982; Salthe, 1985; Ahl and Allen, 1996) in that it explains the complex and impredicative relations among structural and functional elements across different hierarchical levels of organization. I consider functional elements as the parts of the "black box" that define the interaction with the embedding context (black-box is level n, functional parts are at level n−1, the context is level n +1). Each functional compartment is determined by a series of structural elements that are not necessarily homogenous or similar in their biophysical processes.

The assignment of structural elements to a given functional element is a semantic decision: the structural elements must share the same final objective (final cause in the jargon of relational analysis) with the functional element to which it is assigned. Different structural elements—that is, processes associated with a defined land-use typology—mapping onto the same final cause will be accounted in the same functional compartment.

Note that the semantic definition of the relation between structural and functional compartments is subject to a certain level of ambiguity.

Thus, an important feature of MuSIASEM is that the simplification of the information space in a given set of categories of accounting—required to generate a quantitative representation — has to be always checked by the users of the analysis. Moreover, the resulting information space is not semantically closed. The framework of accounting allows an exploration of the option space generated by the complex set of impredicative relations between structural and functional elements across hierarchical levels and scales: it does not deny the existence of chicken-egg paradoxes or ambiguities in the definition of the parts and sub-parts.

Rather it allows to handle them in a transparent way. MuSIASEM deals with self-reference using grammars, that is, by defining a set of expected relations over functional and structural elements that can be tested using contingent analysis.

Changes in external constraints may affect the characteristics of internal processes (top-down causality) or changes in the internal characteristics of the system may redefine the external constraints (bottom-up causality). In this sense, we prefer the term quantitative storytelling over quantitative analysis to stress that numbers generated in this way only have meaning if properly contextualized in relation to (i) the special characteristics of the environment; (ii) the special history of the social-ecological system in question; and (iii) the special research question considered.

MuSIASEM can be used in a diagnostic mode, by analyzing the actual metabolic pattern of a system, or in simulation mode, by examining scenarios (e.g., population growth, technical innovation, changing terms of trade).

In conclusion, the innovative features of this approach are:

1. It is based on an analysis of relations over patterns (processors are profiles of expected inputs and outputs) and not on relations over numbers (e.g., inputs or output) as is the case in conventional models;

2. It integrates quantitative information referring to different hierarchical scales (describing and combining relevant aspects of the system originating from non-equivalent descriptive domains);

3. It integrates quantitative attributes defined according to different dimensions of analysis (economic, social, technical, ecological) and allows the use of geographic information systems;

4. It handles “impredicativity,” that is the ambiguous relation between structural and functional types (chicken-eggs paradox) typically encountered in the analysis of the functioning of complex self-producing systems.

Relational Analysis

Relational system analysis was first introduced by Robert Rosen. In his book “Life Itself” Rosen described the relational theory of systems as: “How any System is organized to the extent that it can be analyzed into or built out of constituent components. The characteristic relations between such constituent components, and between the components and the System as a whole, comprise a new and different approach to science itself, which we may call the relational theory of Systems" (Rosen, 1991). Hence, relational system analysis describes systems as patterns of expected relations over their structural and functional elements developed to fulfill a specific purpose. Relational analysis can be applied to adaptive metabolic networks capable of self-reproduction and self-maintenance, such as social-ecological systems (González-López and Giampietro, 2017). In this case, the emergent property of the system is the ability of the different constituent components to express a functional whole capable of reproducing itself and this emergent property gives the meaning and defines the identity (purpose) of the constituent components (González-López and Giampietro, 2017). In human-made systems (e.g., society) the final cause is given by humans, and therefore the identity of the system is associated with the definition of a goal (what the system is expected to produce).

The interaction with MuSIASEM permits the analysis of non-equivalent domains at different hierarchical levels and holistic analysis of systems. It analyses the relation between the different metabolic patterns of social-ecological systems between themselves, other social-ecological systems and the environment. Relational analysis is based on a set of conceptual building blocks:

The analysis of a system cannot be reduced to the description of its parts: the whole is more than the sum of its parts. For this reason it is essential to define the parts in relation to the role the play in the stabilization (reproduction) of the whole. Moreover, relational information refers to different dimensions of analysis such as the economic and the biophysical. The constituent components of a metabolic systems are the realizations of structural elements capable of expressing an expected set of functions, that when complemented with the set of functions expressed by the other constituent components, do generate the "emergent property" of the whole: the maintenance and reproduction of the identity of the metabolic system.

Functional elements

Functional elements refers to the purposes of the interactions between the parts inside the society (in the black-box) and between the society and its environment (black-box and its context). In the case of activities taking place inside the society the function of a transformation could be that of adjust the quality of the flows supplied and demanded by the various components of the society. The ability of expressing this function entails the organization of the different stocks available and the power capacity installed to extract those stocks, the processing of the different flows and their transport. Because of this relation, a change in the desires and necessities of society translates into a change in the definition of the expected functions to be expressed. Then the goal of changing functions translates into an anticipation of changes in the configuration of the structural elements necessary.

Figure 1 illustrates the relations among the different flows (supply and demand) of the different sectors of society. The flows are qualitative different when moving across different nodes. This set of relations over flows and nodes can be seen as an emergent pattern expressed by the different structural elements that compose the systems to realize an integrated set of functions determining the emergence of the identity of the society. In the resulting metabolic pattern the different output flows must result useful in correspondence with the demanded inputs for the stabilization of societal functions. The ability to supply the right flow in the right quantity in the right place is essential for allowing the whole system to work the way it does – i.e. to exist and reproduce. The reproduction of the whole explains the "why" of the functional elements are doing what they do.

Structural elements

Structural elements describe the performance and the location of each instance of the system. The metabolic characteristics of these nodes are described both in extensive terms (quantity of flows and quantity of fund elements) and intensive terms (ratios of flows over fund elements). The structural part of the systems describes what the system is made of. In resume, how the system does the different thing it does.

Processor

The semantic analog of the "processor" of energy systems is the enzyme for biochemical systems or the production function for economic analysis. In the relational analysis, a processor is a profile of expected inputs and outputs associated with the expression of a specific function (Figure 0-1). The processors of the functional elements of the energy system can be either scaled-up to describe the metabolic pattern of the system as a whole, or scaled-down by considering the characteristics of its lower-level parts. Two important features of the processor are: (i) it provides information that makes it possible to carry out an analysis of the bioeconomic performance, because it mixes together biophysical variables that are relevant for both economic, technical and ecological analysis, and (ii) because of its epistemological ambiguity it makes it possible to transfer information across assessments referring to instances, structural types, functional types and the whole.

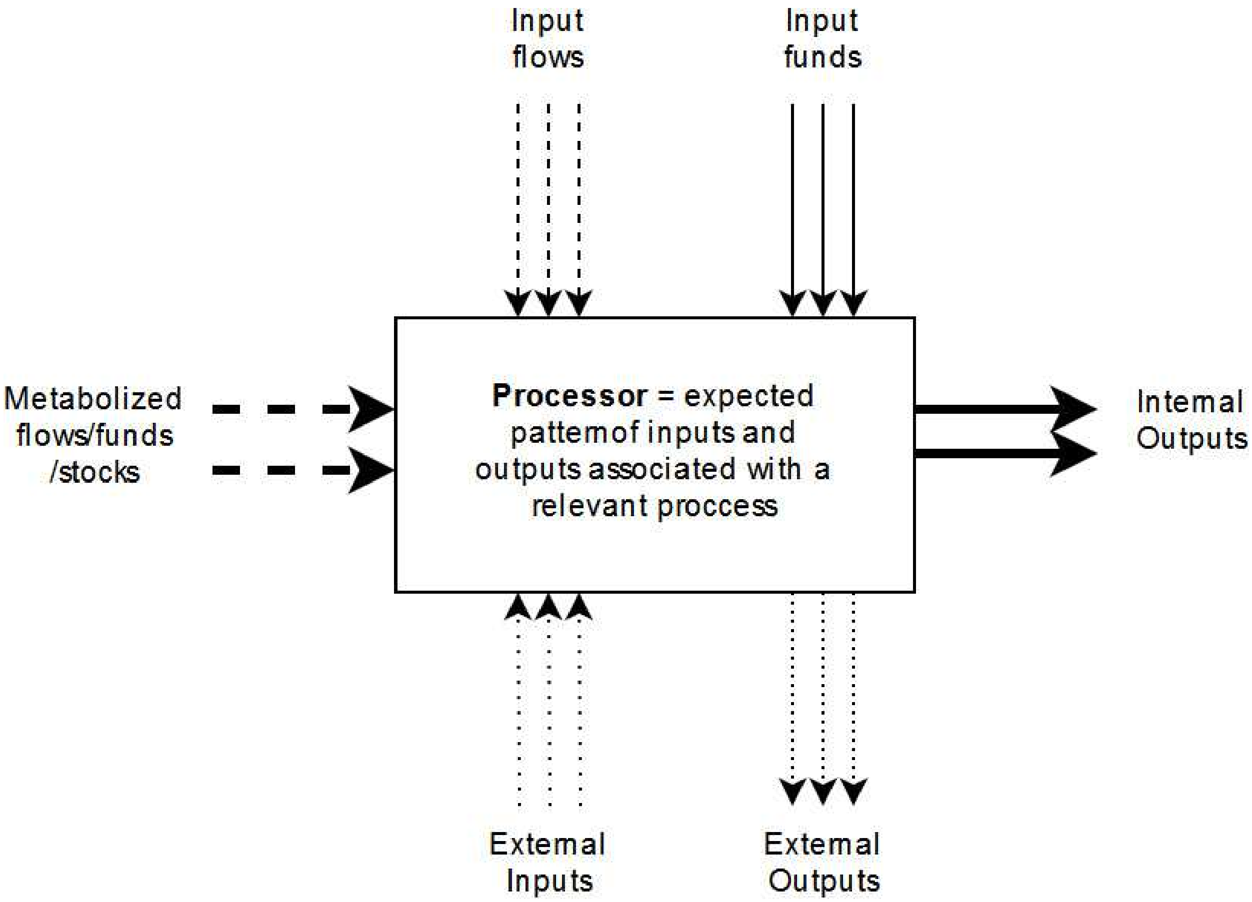

Figure 0-1 Processor description.

The data array structure of the processor defines an expected mix of inputs and outputs associated with a specified process linked to the expression of a given task.

The terminology funds and flows refer to the flow-fund model of Georgescu-Roegen in relation to bioeconomic analysis (Mayumi, 2002). A processor is made of fund elements (quantities of human activity, managed land, power capacity). These quantities of fund elements will remain constant over the time duration of analysis (usually on a yearly basis). Therefore, this information can be used to define the size of the processor. The flow elements describe what the processors do: consuming and producing inputs and outputs (energy, food, water, monetary flows). Flows either appear or disappear during the analysis. Therefore, by using the concept of processor we can define: (1) the size of the functional and structural elements looking at quantities of fund elements; and (2) the qualitative characteristics of these elements (benchmark values) looking at the values of flow/fund ratios—e.g., energy per hour of labor, food per hour of labor, etc.

Chapter I Charcoal metabolism[2]

I.1 Abstract

I propose and illustrate a multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) as a tool to bring nexus thinking into practice. MuSIASEM studies the relations over the structural and functional components of social-ecological systems that determine the entanglement of water, energy, and food flows in a complex metabolic pattern. MuSIASEM simultaneously considers various dimensions and multiple scales of analysis and therefore avoids the predicament of quantitative analysis based on reductionism (one dimension and one scale at the time). The different functional elements of society (the parts) are characterized using the concept of "processor," that is, a profile of expected inputs and outputs associated with the expression of a specific function. The processors of the functional elements of the social-ecological system can be either scaled-up to describe the metabolic pattern of the system or scaled-down by considering the characteristics of its lower-level parts—i.e., the different processors associated with the structural elements required to express the specific function. An analysis of functional elements provides insight into the socio-economic factors that pose internal constraints on the development of the system. An analysis of structural elements makes it possible to study the compatibility of the system with external constraints (availability of natural resources and ecological services) in spatial terms.

I.2 Introduction

Charcoal production plays an important role as a source of energy and cash income for populations of many developing countries. However, charcoal production is increasingly being associated to deforestation and environmental degradation (Mwampamba et al., 2013) and therefore is now often included in the list of

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[2] This chapter builds on the published paper: González-López, R., & Giampietro, M. (2017). Multi-Scale Integrated Analysis of Charcoal Production in Complex Social-Ecological Systems. Frontiers in Environmental Science, 5. https://doi.org/10.3389/fenvs.2017.00054

"dangerous" activities (Zulu, 2010). To seek sustainable solutions, it is important to recognize that charcoal production forms an integral part of a complex network of activities that operates at different scales establishing a bridge between ecosystem services and the supply of key resources such as food, energy, and water (Chidumayo and Gumbo, 2013). Moreover, in many socio-economic circumstances, charcoal production is associated with a rich diversity of stakeholders across its supply chain (Butz, 2013; Ghilardi et al., 2013; Zulu and Richardson, 2013). These various aspects make charcoal production a perfect case study for MuSIASEM. In this work, we adapt the MuSIASEM approach to study the water-energy–food nexus in charcoal-producing rural systems. I use a novel concept, that of "processor" (defined below) that brings the relations among the system's elements into sharper focus. Using this idea of processor, we show in this paper how to characterize the metabolic pattern of water, energy and food of charcoal-producing systems by establishing a relation—in qualitative and quantitative terms— among: (1) the various functional components (e.g., subsistence production, cash crop production, charcoal production, off-farm work) associated with the survival/reproduction of the village (guaranteeing food, energy, and water security); and (2) the related structural elements (e.g., typologies of land-uses, aquifers, off-farm jobs) used to express the functions. In the next section, I first provide the basic features of MuSIASEM.

I.3 General Features of Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism

The MuSIASEM accounting framework organizes quantitative information in reference to different dimensions of analysis—i.e., social, economic, technical, biophysical, ecological—and different hierarchical scales of analysis referring to both socio-economic narratives and an ecological narratives (Madrid-López and Giampietro, 2015). In this way, the information generated can be used to check three dimensions of sustainability:

1. Feasibility—This dimension sees the system (society) as a black-box interacting with its context. Feasibility thus refers to the compatibility of the metabolic system as a whole with processes beyond human control, that is, external constraints imposed by the availability of natural resources and ecosystem services. This dimension involves (i) checking whether the metabolism of the system (seen as a black box) is compatible with the boundary conditions, and (ii) checking the level of openness of the system in terms of trade with other social-ecological systems (the extent of externalization to or dependence on other social-ecological systems);

2. Viability—This dimension looks at the workings inside the black-box to check the interactions among its parts. Viability thus addresses the compatibility of the system in relation to processes under human control (e.g., economic viability, technical viability) by checking whether the interaction of the parts inside the black box is compatible with available technology and know-how;

3. Desirability—This dimension checks whether the characteristics of the metabolic pattern are acceptable to those living inside the system (the desirability of the metabolic pattern directly affects the stability of the social fabric).

MuSIASEM basically consists of a relational analysis of the functional and structural elements of a social-ecological system that together determine its metabolic pattern of water, energy, and food. The concept of metabolism is commonly associated to the human body to represent the complex processes converting food into the energy and building blocks required to maintain its structure and functions. However, the concept of metabolism can also be and indeed has been applied to social-ecological systems (Ostwald, 1907, 1911; Lotka, 1922, 1956; Soddy, 1926; Zipf, 1941; White, 1943; Cottrell, 1955). Complex societies exhibit a mechanism of reproduction and maintenance similar to that of the human body. They extract and use a mix of energy and material inputs from their environment to express the functions required for preserving their identity. Along these premises, a new scientific field has emerged that is based on the study of "societal (or social) metabolism" (Wolman, 1965; Martinez-Alier, 1987; Fischer-Kowalski and Hüttler, 1998; Daniels, 2002; Swyngedouw, 2006; Giampietro et al., 2009; Broto et al., 2012; Giampietro, 2014). Metabolic pattern refers to the expected profile of inputs (taken from the environment) and outputs (discharged into the environment) associated to the set of functions required to reproduce the identity of a given social-ecological system (Giampietro et al., 2011). The concept of metabolic pattern neatly shows that the nexus between water, energy, and food is determined by forced relations among the structural and functional elements of a complex system. The term "relational analysis" (Rosen, 1958, 1985; Louie, 2009, 2013) indicates the existence of expected patterns of relations over the elements of metabolic networks that are capable of self-reproduction and self-maintenance. It implies a distinction between: (i) inputs and outputs remaining inside the self-organizing system; and (ii) inputs and outputs exchanged with the context. MuSIASEM also borrows from hierarchy theory (Koestler, 1968; Whyte et al., 1969; Allen and Starr, 1982; Salthe, 1985; Ahl and Allen, 1996) in that it explains the complex and impredicative relations among structural and functional elements across different hierarchical levels of organization. In particular, we consider functional elements as the parts of the "black-box" that define the interaction with the embedding context (black-box is level n, functional parts are at level n−1, the context is level n +1). Each functional compartment is determined by a series of structural elements that are not necessarily homogenous or similar in their biophysical processes (see Figure 1). For example, a functional compartment (vegetable production) may be composed of different combinations of structural elements (processes producing tomatoes, egg-plants, zucchini).

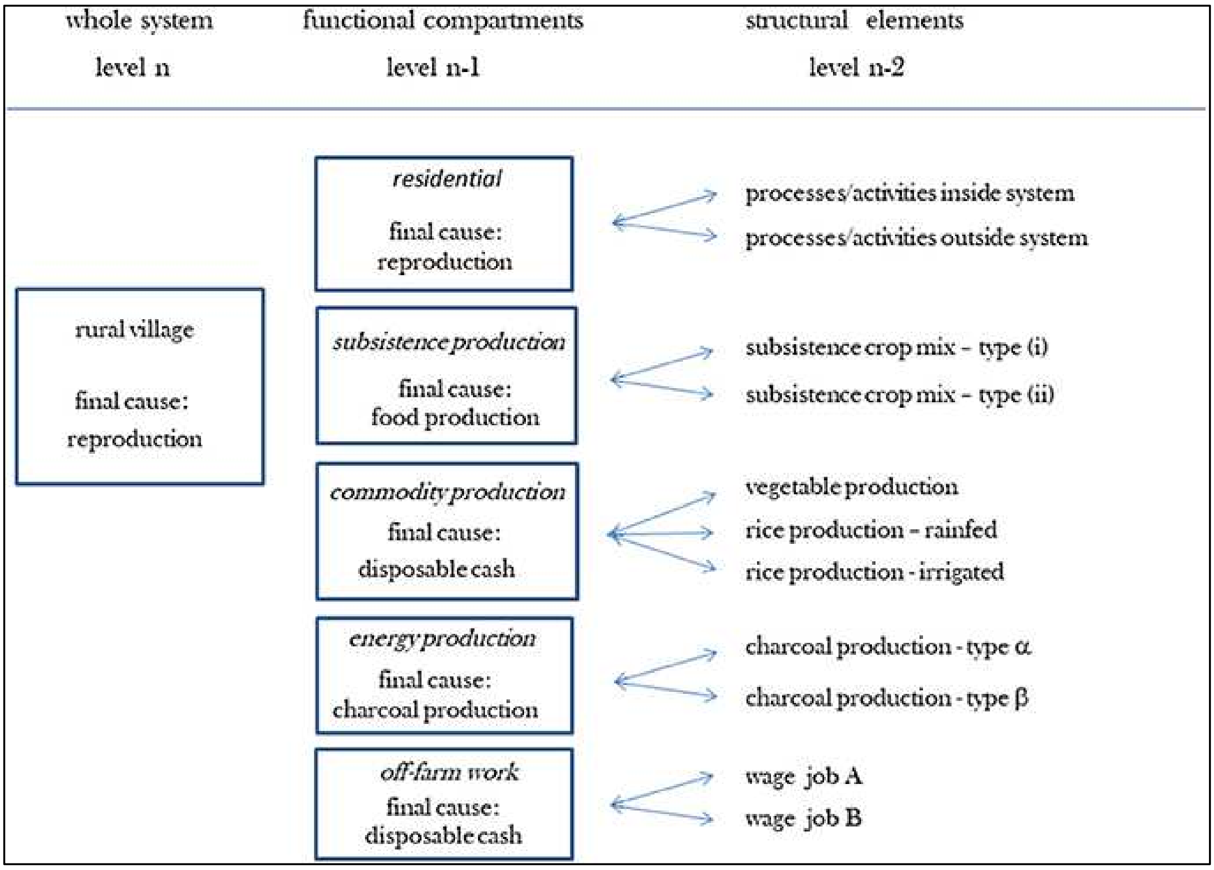

Figure I-1 Hierarchical organization of the system.

The definition of the function of the whole (on the left) translates into a definition of functions for the functional compartments in the middle, using structural elements to carry out their tasks at the level n-2 (on the right).

The assignment of structural elements to a given functional element is a semantic decision: the structural elements must share the same final objective (final cause in the jargon of relational analysis) with the functional element to which it is assigned. For example, in Figure I-1, vegetable production and rice production belong to the same functional compartment (cash crop production). Different structural elements—that is, processes associated with a defined land-use typology—mapping onto the same final cause will be accounted in the same functional compartment. The structural elements are considered as sub-parts of the functional components as described in Figure I-1(structural parts are defined at level n−2, functional parts at level n−1, and the black-box at level n).

Note that the semantic definition of the relation between structural and functional compartments is subject to a certain level of ambiguity. For example rice production can be mapped onto two different functional compartments, "subsistence production" and "cash crop/commodity production"; charcoal production can be mapped onto "energy production" or "cash crop/commodity production." In the same way, the final cause—getting disposable cash—can be obtained in two different ways, relating to two structural elements of different nature: on-farm production requiring land use allocation and off-farm work not requiring land allocation within the system boundaries. All these "bifurcations" can be handled by the accounting framework of MuSIASEM. In fact, MuSIASEM accounting entails a constraint of congruence to avoid double counting (and a messy representation). The sum of the relative sizes of the flows (energy, water, food, and money) and the funds (hours of human activity and hectares of land use) associated with the functional compartments and structural elements (defined at levels $n-1$ and level $n-2$, respectively) must be equal to the total amount of flow and fund elements defined at level n. For example, when the process of charcoal production generates an input (energy flow) consumed by the village, we must include the funds and the flows associated with this production to the final cause of producing energy. On the contrary if the charcoal is sold on the market then the funds and flows associated with this process are included in the functional compartment "getting disposable cash." In fact, when charcoal is produced and sold it does not belong to the energetic metabolism of the village, it becomes just a commodity. In relation to this point, the conditions of congruence—the size of all the flows and funds must remain the same when moving across different levels of analysis—guarantee coherence in the analysis.

Thus, an important feature of MuSIASEM is that the simplification of the information space in a given set of categories of accounting—required to generate a quantitative representation—is not semantically closed, as is the case with conventional models. The framework of accounting allows an exploration of the option space generated by the complex set of impredicative relations between structural and functional elements across hierarchical levels and scales: it does not deny the existence of chicken-egg paradoxes or ambiguities in the definition of the parts and sub-parts, rather it handles them. MuSIASEM deals with impredicativity through the use of grammars, that is, a set of expected relations over functional and structural elements that is semantically open. In fact, it may be that changes in external constraints will affect the characteristics of internal processes (top-down causality) or that changes in the internal characteristics of the system will redefine the external constraints (bottom-up causality). In this sense, we prefer the term quantitative storytelling over quantitative analysis to stress that numbers generated in this way only have meaning if properly contextualized in relation to: (i) the special characteristics of the environment; (ii) the special history of the social-ecological system in question; and (iii) the special research question considered.

MuSIASEM can be used in a diagnostic mode, by analyzing the actual metabolic pattern of a system, or in simulation mode, by examining scenarios (e.g., population growth, technical innovation, changing terms of trade).

In conclusion the innovative features of this approach are:

1. It is based on an analysis of relations over patterns (processors are profiles of expected inputs and outputs) and not on relations over numbers (e.g., inputs or output) as is the case in conventional models;

2. It integrates quantitative information referring to different hierarchical scales (describing and combining relevant aspects of the system originating from non-equivalent descriptive domains);

3. It integrates quantitative attributes defined according to different dimensions of analysis (economic, social, technical, ecological) and allows the use of geographic information systems;

4. It handles "impredicativity," that is the ambiguous relation between structural and functional types (chicken-eggs paradox) typically encountered in the analysis of the functioning of complex self-producing systems.

The Idea of Processors

An important novel aspect of the approach proposed here compared to earlier work is the use of processors to assign an identity to the metabolic elements of the system. Any metabolic element of a social-ecological system, whether a functional compartment or a structural element, is an open system in itself that expresses an expected pattern of "behavior" in terms of: (i) consumption of inputs; (ii) expression of a useful function coinciding with the supply of useful output(s); and (iii) generation of unwanted by-products. The semantic analog of the "processor" of social-ecological systems is the enzyme for biochemical systems or the production function for economic analysis. The basic idea is that a specific pattern of inputs can be associated to the generation of a specific pattern of outputs. Depending on the scale considered, the expected behavior may be either: (i) reproducing itself (if we are considering the metabolic system as a whole); (ii) expressing a useful function needed to stabilize the larger metabolic system to which the element belongs (if we are considering a functional element); or (iii) transforming a profile of inputs into an expected profile of outputs (if we are considering a structural element making up a functional element). Metabolic elements can be defined as functional elements, when their characteristics are determined by processes taking place on the level above (top-down causality), or structural elements, when their characteristics are determined by processes taking place on the level below (bottom-up causality).

Thus, we describe each metabolic element (either functional or structural) as a processor that establishes a relation between: (i) internal inputs and internal outputs, and (ii) external inputs and external outputs. "Internal" refers to two different typologies of elements that are consumed or produced (flows) and maintained (funds) by the society (societal metabolism). In the jargon of life cycle analysis (LCA), internal elements are described as operating in the "technosphere" and therefore they refer to inputs and outputs determined by processes that are under human control and remaining within the borders of the socio-economic systems. "External" refers to flows that are produced or received by processes outside human control, that is, natural processes and ecosystem services (ecosystem metabolism). In the jargon of LCA these flows are considered as "coming from" or "going to" the biosphere.

As illustrated in Figure I-2 a processor is therefore associated with five sets of inputs/outputs:

- n1: Internal inputs—required flows under human control (e.g., electricity, fuels, blue water, food, monetary flows):
- n2: Internal inputs—required funds under human control (e.g., hours of human labor, hectares of land use, power capacity):
- n3: External inputs—required flows extracted from ecosystems (e.g., green water, water extracted from aquifers to generate blue water, ecological services):
- n4: External outputs—flows that must be discharged into ecosystems (e.g., pollutants, nitrogen from fertilizers, solid waste, GHG emissions):
- n5: Internal outputs—useful flows or funds generated by metabolic elements and used by other elements in the technosphere (e.g., the useful products of functional and structural elements—supply of charcoal, rice, disposable cash).

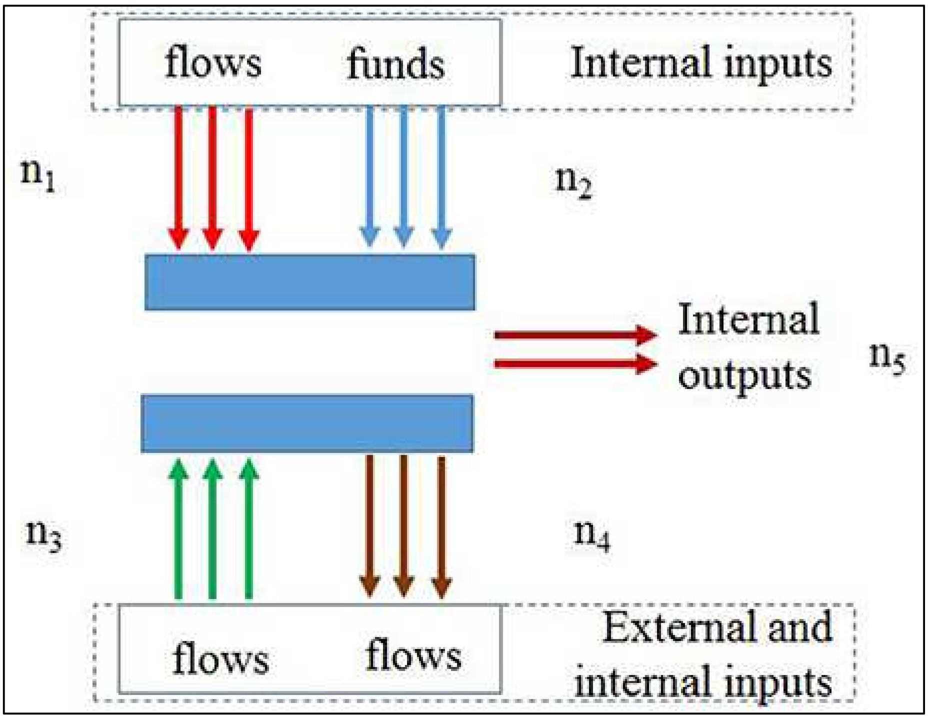

Figure I-2Conceptualization of the expected pattern of inputs and outputs in a processor.

Inputs and outputs remaining in the technosphere are internal, those getting from and to the biosphere are external.

The terminology funds and flows refers to the flow-fund model of Georgescu-Roegen in relation to bioeconomic analysis (Mayumi, 2002). A processor (Figure I-3), is made of fund elements (inputs of human activity, managed land, power capacity), and this amount of fund elements will remain constant over the time duration of analysis (usually on a year basis). This information can be used to define the size of the processor. The flow elements describe what the processors do: consuming and producing inputs and outputs (energy, food, water, monetary flows). Flows either appear or disappear during the analysis. Therefore, by using the concept of processor we can define: (1) the size of the functional and structural elements looking at quantities of fund elements; and (2) the qualitative characteristics of these elements (benchmark values) looking at the values of flow/fund ratios—e.g., energy per hour of labor, food per hour of labor, etc.

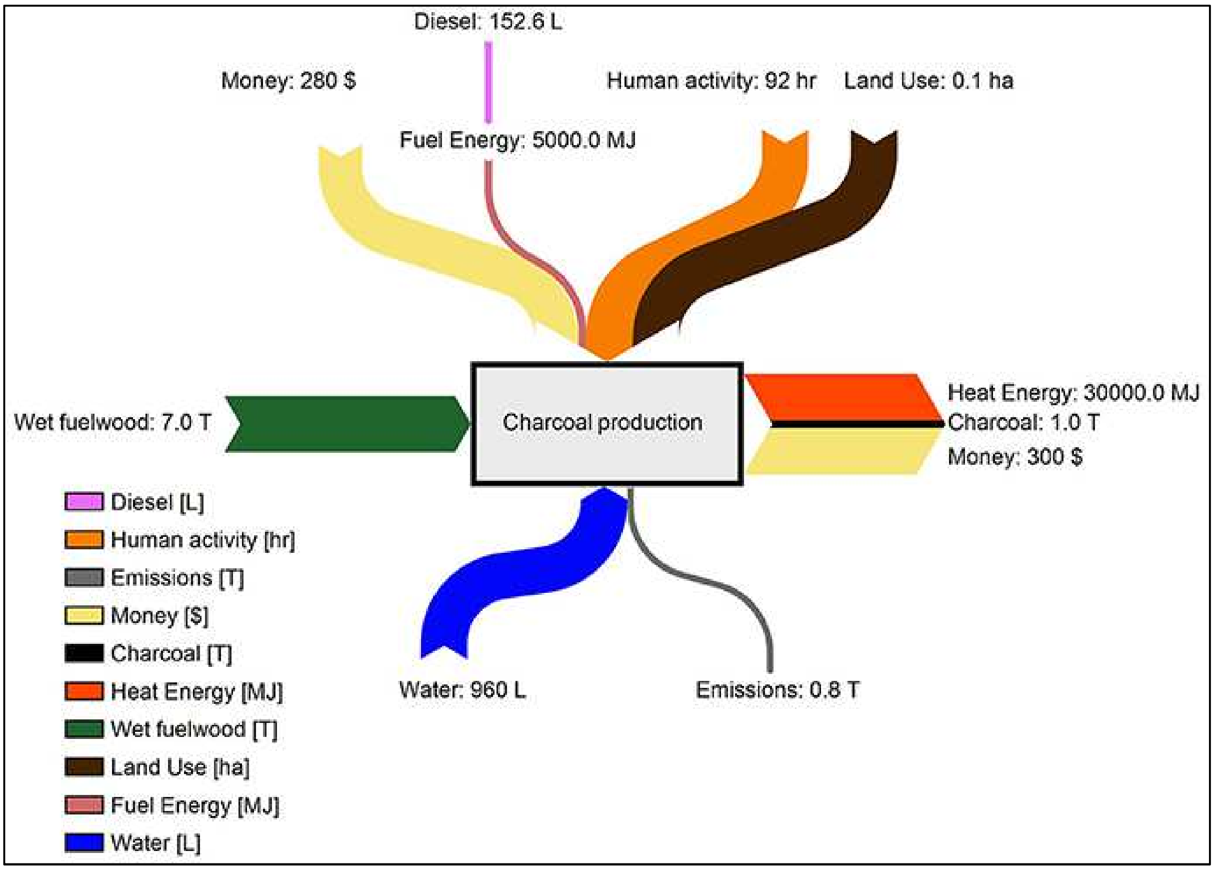

Figure I-3 Schematic representation of the charcoal production processor. Data are made up for the purpose of illustration.

A representation based on processors makes it possible to describe social-ecological systems across different scales. In fact, the characteristics of the different processors of functional elements can be scaled-up to describe the characteristics of the whole village. This translates into defining a higher-level processor by scaling-up the relative quantities of inputs and outputs. The characterization of the given set of relations across scales is illustrated in Figure I-4. In order to obtain the scaling, it is essential that the sum of the sizes of funds and flows described in the functional elements is equal to the size of funds and flows (per category) described at the level of the whole. The identification and definition of functional elements requires assigning an identity to the different socio-economic sectors or activities (a definition of why are they needed).

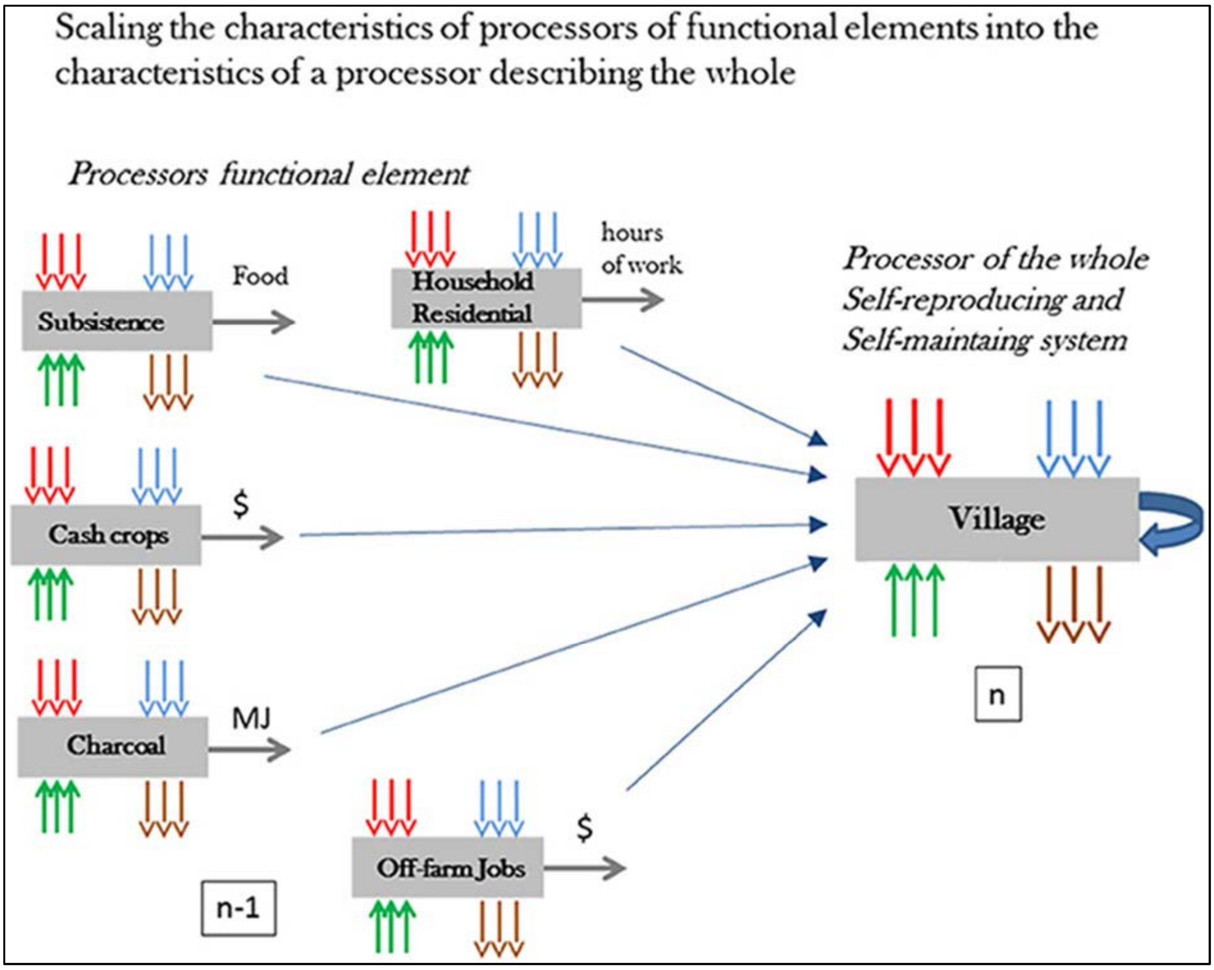

Figure I-4 The characteristics of a processor describing the whole society (on the right) are explained using the characteristics of the processors describing functional elements (on the left).

I.4 Relational Analysis Over Functional Elements

In Figure 4 I propose a set of functional elements associated with a charcoal-producing village. As discussed earlier, functional elements describe the social-ecological system top-down. They explain what the system does in terms of socio-economic activities (what/why): charcoal production (either energy supply or getting disposable cash through commodity production), off-farm work (getting disposable cash through wages), and residential activities (reproducing the fund element “people”). Since this method of representation is semantically open, other functional elements may be added to this set (e.g., cultural, religious activities). What is important is to re-adjust, after the introduction of a new set of the functional and structural element, the profile of allocation of funds and flows to maintain the congruence of the relative sizes and relative paces and densities across the different representations across levels. As a matter of fact, the "identity" of the social-ecological system in terms of a set of functional elements should be defined based on participatory processes involving the inhabitants of the system.

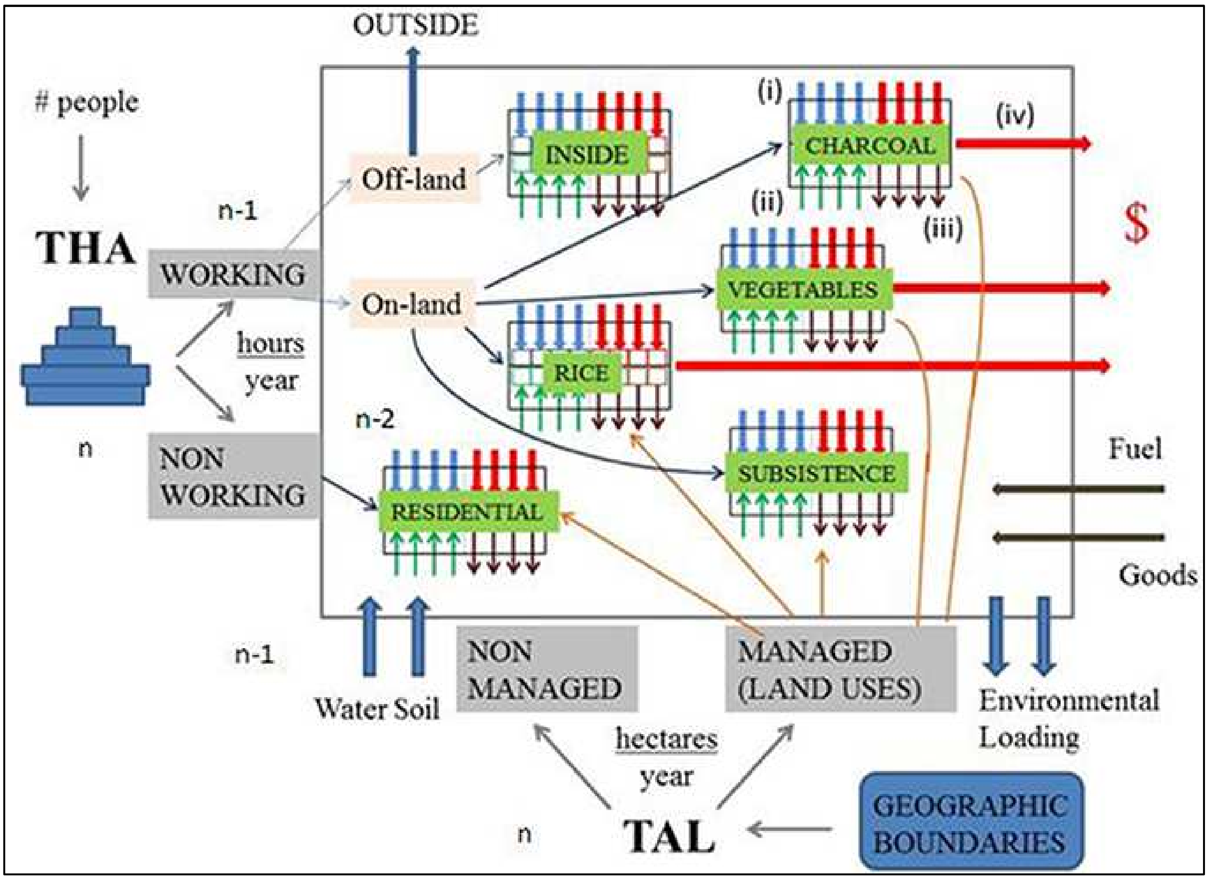

Figure I-5 Representation of the functional elements for a charcoal-producing village.

Each activity is associated with a processor determining a set of expected relations between inputs, outputs, wastes, and emissions. The overall metabolic pattern can be assessed against the constraints provided by the limited availability of human activity (THA) and available land (TAL).

The definition of the set of functional elements, the definition of their relative sizes, and the definition of the metabolic profile of the various flows (e.g., water, energy, money) in each of the functional elements generate mutual information in the system, also called a "Sudoku effect" in analogy with the Sudoku game (Giampietro and Bukkens, 2015). Sudoku is a popular number puzzle in which one can infer the solution based on a set of congruence constraints and the information already given. Note that the size of the funds and the flows in the processor of the different functional compartments must be compatible with the size and the flows of the set of processors making up the whole (system closure). The quantification of the characteristics of the various processors in relation to the processor of the whole (after considering imports and exports) permits us to study the existence of sets of forced relations ("playing the Sudoku game").

Using the concept of processor, we can define the total size of the funds, in this example: total human activity measured in hours per year (THA = population × 8,760) and total available land within the geographic boundaries (TAL), measured in hectares (see Figure I-5). This is the overall size of the village (at level n) should be divided among the lower-level functional elements (level $n-1$). Both THA and TAL must be distributed over the different functional elements (the categories of human activity and land uses associated with the different processors) in accordance with the socio-economic organization. This entails a competition for the use of these funds across different functional compartments. Therefore, each investment in any one of the functional elements can be considered to have an "opportunity cost" for society (the same amount of funds could be used for a different purpose).

An additional constraint is represented by the qualitative characteristics of the functions expressed by the functional elements. For instance, crop production can only take place on arable land. So additional categories, such as managed land (land uses) and non-managed land, need to be used for organizing the accounting (see Figure I-5). This explains why an analysis of functional elements requires also a simultaneous analysis of structural elements carried out to a finer grain (at a smaller scale). The same applies for the fund human activity: Human beings need a given amount of sleep and personal care (non-working time), heavy work requiring a high level of power can only be carried out by male adults or animal power, etc. It should be noted that by looking at the analysis of functional elements, we can get a diagnostic analysis of the relations between funds and flows inside and across different functional elements. For example, one can calculate how much water (flow), managed land (fund), and human labor (fund) is required or how much pollution is generated by a given processor. However, based on a relational analysis of functional elements only, one cannot define the exact location of the associated activities. To have the exact location in space of a specific biophysical process (described by its specific processor) we should look at the corresponding structural element(s). This can be achieved using a layer in GIS of all the land uses (e.g., typologies of crop production) mapping onto the same functional type (e.g., commodity production). In this way, we can handle a typical predicament of integrated assessment: (i) the accounting of economic flows (internal inputs and outputs coming and going into the technosphere) can be "translated" into economic variables considering the costs and revenues—prices. But this accounting is not directly associated with specific locations; (ii) the assessment of environmental impacts requires us to locate the exact position of the land use.

In Figure I-5 we can also see the inflows and outflows resulting from market transactions. Note that this graph is just a skeleton for the organization of the accounting. The various flows are indicated in semantic terms but can be quantified adopting different choices of proxy variables. For instance, food may be quantified in terms of kg of food products (potatoes, beef, papaya, etc.) or kcal of nutrients (proteins, carbohydrates, calories). The same applies to water (blue water and green water) or energy (charcoal, gasoline, or wood). In MuSIASEM, benchmarks, such as charcoal produced per hour of labor, money earned per hectare, food required per person per day, water extraction from the aquifer per day, are used to assess the relative flows. In this way, it becomes possible to summarize the balance of the system (whole vs. the sum of all the functional elements) in relation to the chosen metric for quantifying energy, food, water, human activity, land use, and money flows. This balance must consider the distinction between flows derived from inside the village and those from outside (imports). This diagnostic analysis is a good starting point to have the big picture of the factors (drivers, states) determining the sustainability on the socio-economic side.

I.5 Relational Analysis Over Structural Elements

Structural elements are elements expressing an expected metabolic pattern of inputs and outputs associated with a known process. They have an external referent independent of their function guaranteeing the reliability of the expression of the pattern (e.g., a common blueprint or know-how determining the characteristics of the process). Examples of structural elements are a hectare of rice cultivated with a given technology, a job providing a known wage, a pattern of behavior of members of a household when out of work. Structural elements are associated with the expression of a specific typology of process and therefore with the expression of an expected profile of inputs and outputs at a given scale. In general, the scale of the structural elements is smaller than that of the corresponding functional type.

Indeed, several structural types can feed into one functional type. For instance, as illustrated in Figure I-6, all the hectares of cropland used to cultivate rice with a specific technique (e.g., rainfed) and all the hectares of cropland used to cultivate rice with another technique (e.g., irrigated) can be aggregated into another category of accounting that is "rice production." In turn, the two structural elements "rice production" and "vegetable production"—referring to actual processes taking place in specific locations (hectares of land use) with known modalities (yields and labor productivity)—can be aggregated into the functional element "cash crop production."

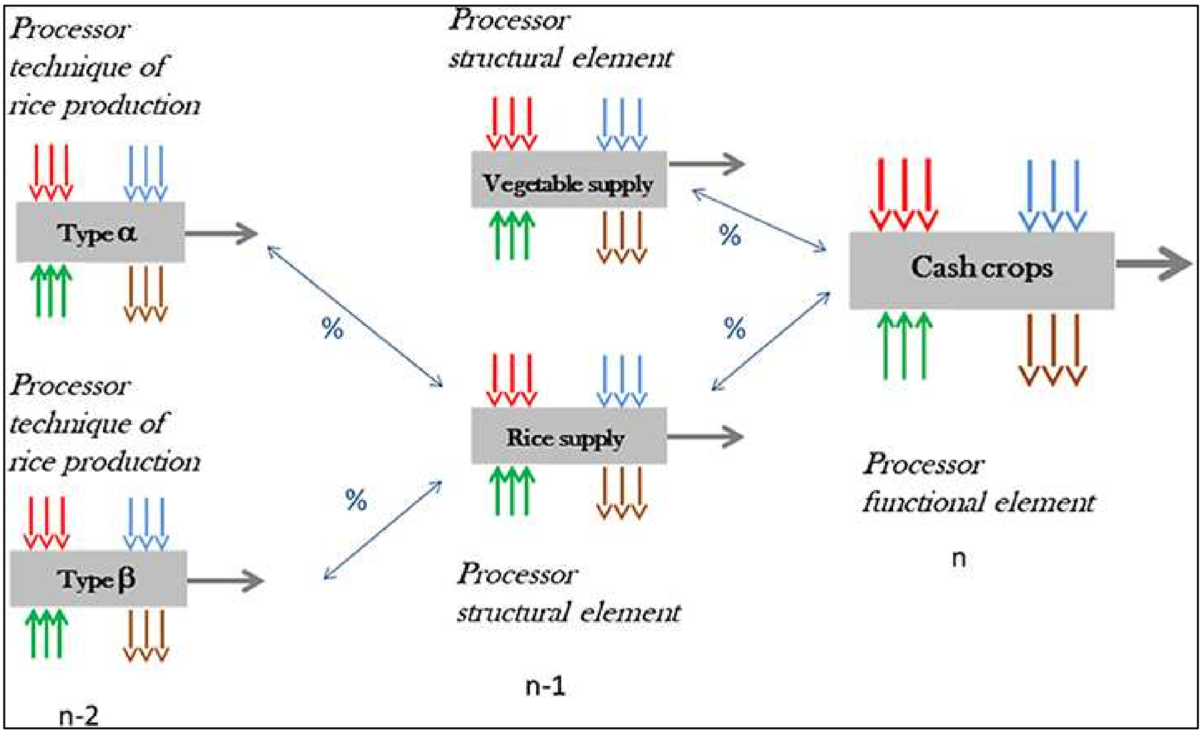

Figure I-6 Scaling the representation starting from the characteristics of production techniques (on the left) scaled into the characteristics of structural elements (in the middle) scaled to the characteristics of functional elements (on the right). The scaling can go in the two directions.

For the operation of scaling down (moving from right to left in Figure I-6), it is necessary to obtain information on the characteristics of the structural elements at the local scale. In this way, it becomes possible to generate the analysis shown in Figure I-7 in which different land uses map onto the same category of structural elements. This procedure allows us to study the existence of external constraints—availability and suitability of land, availability of water, the effect of pollution, destruction of habitat, etc.

Vice versa, to be able to interpret the information given by technical coefficients defined at the local level of land uses—the characteristics of structural elements defined by processors—we must scale them up to the level of functional elements (moving from left to right in Figure I-6. For instance, in this way, we can examine how the flows observed at the local level of structural elements "translate" into economic flows associated with imports and exports of inputs and outputs at the level of the whole village. At this point, the importance of handling impredicativity becomes evident. We can use the established set of relations either: (i) to assess the characteristics that would be required by the mix of processors of structural elements (the pattern of production) to achieve the economic performance required by the functional elements, or (ii) to assess what type of economic performance can be achieved by the functional element, given the characteristics and the mix of lower-level structural elements.

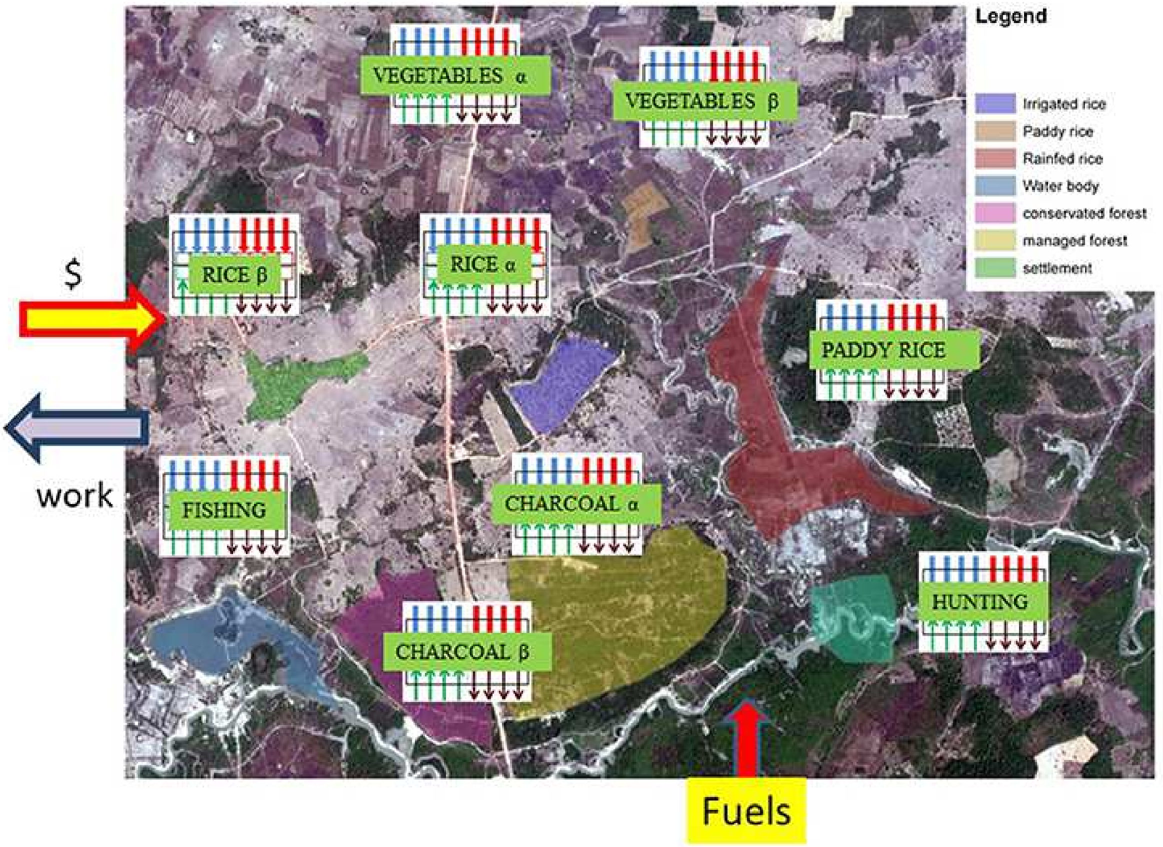

Figure I-7 Representation of structural elements (green squares) for a hypothetical charcoal-producing village. For each activity, I show different typologies having different input requirements.

The multi-scale analysis permits us to elucidate the nature of costs and benefits at the local scale (e.g., between different technologies to extract water: water pumps powered by wind or diesel), the relevance of these costs in the overall budget of the households at a mesoscale, to finally arrive at how the different performances of households affect the characteristics of the whole village.

In simulation mode, processors can be used to compare the effect of changes in the relative size of structural types that feed into the same functional type. For example, we can compare the profiles of inputs and outputs associated with 1 ton of rice produced by different techniques (α vs. β) and make projections on how a different mix of the production techniques will affect the land use and overall flows of energy, water, and food at the village level. Trade-offs (e.g., 1 ton of rice α requires more energy than rice β, but less water) can then be evaluated within a larger analysis of the metabolic pattern in relation to the indirect effects that an adjustment in one functional element (rice production) can have on the others in terms of changes in the allocation of land-use, overall production of food for self-consumption or generation of cash income.

An analysis based on structural types and land-use analysis makes biophysical constraints better visible (Serrano-Tovar and Giampietro, 2014). For example, flooded areas are good only for rice production but not for vegetable production. Also, distance to the fields is an important factor in determining labor productivity because commuting diminishes the time available for other activities. Finally, an analysis of land use and structural elements allows us to better appreciate how the flows of energy, water, and biomass metabolized by processes under human control affect (in negative ways) the ability of the embedding natural ecosystems to express their metabolic pattern of flows of energy, water, and biomass (Lomas and Giampietro, 2017).

I.6 Discussion and Conclusions

In relation to charcoal production in rural villages, MuSIASEM can result extremely useful in that it characterizes the functional elements in relation to human time (activity) allocation (the hours of labor/activity required to express the different functions). In many charcoal-producing subsistence villages, the opportunity-cost of human time is a key factor determining the observed pattern of activities. Examples are the trade-offs between subsistence vs. cash-crops and child labor vs. education.

For instance, in the case of the Dong Khuai village in Laos (Yokoyama et al., 2014), an increasing share of the villagers goes working outside the village to bring money inside. The same final cause "getting disposable cash" can be obtained from two different functional elements: producing commodities (that may include charcoal!), something requiring land-uses, or working outside the village, not requiring land uses. Population growth and the movement to a market economy reduce the amount of land available inside the village to collect wood and produce charcoal and increase the opportunity cost of labor. When pressured by these two drivers, villagers tend to invest relatively more human time in earning money through off-farm work and then use the money generated in this way to buy LPG gas. The trade-offs of this substitution can also be assessed by considering the final cause of the functional element "producing energy" and comparing the two structural processes "charcoal production" vs. "generation of income to purchase LPG" that can fulfill the same function. Buying LPG has a much lower opportunity cost of human time than making charcoal, but it increases the dependence on the availability of off-farm jobs and the risk in case of fluctuations in gas prices. These two conditions are beyond the control of the villagers and therefore this trade-off can only be properly assessed at a larger hierarchical level considering a larger scale (the relation between the village and its socio-economic context). The same dilemma is faced in relation to food security. Abandoning self-sufficiency, obtained through the functional compartment "subsistence production," in favor of a fully monetarized economic process—getting cash through wages to buy food—may provide an improvement in living conditions but it may also increase the risks for the villagers.

In this example, we see that the production of charcoal and food can be considered in relation to different perspectives ("food and energy" vs. "disposable cash"). The analysis of the resulting trade-offs depends on the set of relations between the size and the characteristics of the structural and functional elements in the metabolic pattern. How much charcoal and food can be sold, what is the "opportunity cost" of the land, labor and other inputs to be invested in their production, how much land and labor is available. The internal competition for production factors can be related to the problem of children forced to help their parents to collect wood (Yuichiro et al., 2009). When the time of the children is needed to collect wood, we deal with a community constrained by the requirement of labor to remain at a low level of education and leisure.

In conclusion, I illustrated that the main logic of the approach consists in establishing a relation among different hierarchical levels and different dimensions of analysis. Characterizing functional elements in relation to the whole system (levels $n+1$, n, $n-1$) the approach bridges the biophysical and economic dimension of sustainability. Characterizing structural elements (levels $n-2$, $n-1$, n) the approach links the technical and ecological dimension of sustainability. The proposed quantitative representation organized over a specified set of functional and structural elements forces the analyst to address the "why, what and how questions": What is produced and consumed? How are goods and services produced and consumed and by whom? Why these goods and services and why these modalities? Why does society express this specific pattern of functions and not another? A transparent analysis of the what, how and why questions represent an effective application of nexus thinking in the form of quantitative storytelling and a good starting point to improve research and policy approaches in complex landscapes.

Chapter II Oil & Gas metabolism[3]

II.1 Abstract

This chapter describes a novel toolkit to analyze energy systems in relation to the bio-economic and environmental performance of society. It is illustrated with data from the oil and gas sector of Mexico. The approach combines relational analysis (as developed in theoretical biology) and Multi-Scale Integrated Assessment of Societal and Ecosystem Metabolism (MuSIASEM). It integrates two non-equivalent views of the functioning of the oil and gas system starting from the identification and description of the relations between functional and structural elements. The metabolic pattern of the energy system is described as a sequential pathway generated by different functional elements (e.g., extraction, refining, transportation), each of which is made up of different structural elements (e.g., plants adopting different extraction techniques, diverse types of refineries, different methods of transportation), and operating at a given level of openness (imports and exports). The relations found over the elements of the energy system are described both in functional terms (what/why) and in spatial terms (where/how). The policy relevance of the information generated is discussed in relation to the Mexican Energy Reform.

II.2 Introduction

Energy has played an important role in human evolution, determining the pace of human activities within the economic process and the expression of complex societal functions (Cottrell, 1955; Georgescu-Roegen, 1971; Giampietro, Mayumi, & Ramos-Martin, 2009; Giampietro, Mayumi, & Sorman, 2011; Hall & Ramírez-Pascualli, 2012; Ostwald, 1907; Slesser & King, 2002; Smil, 2003, 2008a, 2008b; Soddy, 1926; White, 1943). One of the most important factors leading to the economic prosperity

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[3] This chapter builds on the published paper: González-López, R., & Giampietro, M. (2018). Relational Analysis of the oil and gas sector of Mexico: Implications for Mexico's Energy Reform. Energy. https://doi.org/10.1016/j.energy.2018.04.134

of contemporary society has undoubtedly been the abundant availability of cheap oil (Cottrell, 1955; Hall & Klitgaard, 2011; Smil, 2008a). The concept of peak oil points at a pending crisis of the fossil-fuel-based economy and the need for readjusting to new biophysical constraints (Heinberg, 2009; Hubbert, 1948; Odum, 2013). The consequences of peak oil are complex. Indeed, peak oil is not only about finding alternative energy sources, but also about readjustments of the economy and environmental impacts. While we can no longer rely on increasing supplies of fossil energy to power the growth of a carbon-based economy, there are many reasons to doubt that a quick and massive substitution of fossil energy with alternative energies is possible. Especially replacing oil as the main source of liquid fuels is a formidable challenge.

Current energy research and policies tend to focus either on increasing efficiency in the use of energy carriers in society (demand-side) or on the substitution of fossil fuels by renewable energy sources (Alpizar–Castro & Rodríguez–Monroy, 2016; Smil, 2008a). Relatively little research has been done on the biophysical performance of the oil and gas sector itself (Masnadi & Brandt, 2017). This is surprising as most oil-producing countries are not only progressively investing more money but also using more energy in fossil fuel exploration, extraction, processing, and transportation (Lazarus, Erickson, Tempest, & Lazarus, 2015). The resulting growing level of emissions per unit of output from the oil and gas sector is expected to exacerbate future global carbon emission levels (Masnadi & Brandt, 2017).

To fill this gap, this paper proposes an integrated assessment of the different processes taking place simultaneously at different hierarchical levels of organization in the network of energy transformations in the fossil fuel sector. Data of the Mexican oil and gas sector is used to illustrate the approach. The integrated analysis is obtained by combining two non-equivalent views (structural and functional) across different levels of analysis. The different functional elements of the sector are characterized using the concept of "processor"; the structural parts are characterized by the metabolic pattern of inputs and outputs for different typologies of technologies or regions in spatial terms. In addition, variables belonging to different dimensions of analysis are included in the analysis, while also differentiating between different types of energy qualities. Quantitative storytelling is employed to contextualize numbers in relation to energy policy. Our approach reflects the biophysical costs of the oil and gas sector and does not consider the prices of oil and gas in the market. I think that this is essential for a robust analysis that helps to understand the energy sovereignty of a country, given the volatile and unpredictable prices of oil in the market (Kallis & Sager, 2017; Tverberg, 2012).

The Mexican oil and gas sector represents an interesting case to illustrate the approach. Mexico is one of the largest producers of oil and petroleum liquids in the world. Half of the oil domestically produced is currently exported. In 2015, the oil and gas sector of Mexico generated almost 5% of the GDP and 33% of public revenues (Alpizar-Castro & Rodríguez-Monroy, 2016). However, since 2004 Mexico's oil & gas production has been steadily decreasing due to a decline in the productivity of the Cantarell oil field. Current energy reform, ending the 75-year-old state regulation, has opened Mexico's oil and gas market to private investors. One of the main aims of this reform is to increase the production of oil & gas through private investment (Alpizar–Castro & Rodríguez–Monroy, 2016; Guevara, Córdoba, García, & Bouchain, 2014). At the same time, Mexico's climate policy must be addressed as PEMEX, the Mexican oil state company, is among the top ten fossil fuel producer's emitters in the world (Griffin, 2017; Rowlands, 2000).

II.3 Methodology

Theoretical pillars

The proposed approach combines Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) (Aragão and Giampietro, 2016; Diaz-Maurin and Giampietro, 2013; Giampietro et al., 2009; Sorman and Giampietro, 2011; Velasco-Fernández et al., 2015) with principles of relational system analysis (Louie, 2009, 2013; Rosen, 1958, 1985). MuSIASEM is a logic of accounting based on concepts derived from bio-economics and complex systems theory (Giampietro, 2014; Giampietro et al., 2009). It keeps congruence over quantitative assessments across different compartments (sectors) of society at various hierarchical levels of organization and combines non-equivalent descriptions of a given complex system (Aragão and Giampietro, 2016; Diaz-Maurin and Giampietro, 2013; Giampietro et al., 2009).

Relational system analysis was first introduced by Robert Rosen. In his book "Life Itself" Rosen described relational theory of systems as: "How any System is organized to the extent that it can be analyzed into or built out of constituent components. The characteristic relationships between such constituent components, and between the components and the System as a whole, comprise a new and different approach to science itself, which we may call the relational theory of Systems" (Rosen, 1991). Hence, relational system analysis describes systems as patterns of expected relations over their structural and functional elements developed to fulfill a specific purpose. Relational analysis can be applied to adaptive metabolic networks capable of self-reproduction and self-maintenance, such as social-ecological systems (González-López and Giampietro, 2017). In this case the emergent property of the system is the ability of the different constituent components to express a functional whole capable of reproducing itself and this emergent property gives the meaning and defines the identity (purpose) of the constituent components (González-López and Giampietro, 2017). In human-made systems (e.g., society) the final cause is given by humans, and therefore the identity of the system is associated with the definition of a goal (what the system is expected to produce).

Relational analysis of energy systems

According to the principles of relational analysis, the performance of the oil and gas sector of a given country does affect and, at the same time, depends on the role it is expected to play in the rest of the economy. The oil and gas sector is shaped by: (i) external constraints determined by boundary conditions, that is, the availability and quality of natural resources used as primary energy sources; (ii) internal constraints, imposed by the specific requirements of the other economic sectors, in terms of what energy carriers (both in quantity and quality) the oil and gas sector is expected to supply; and (iii) the technological capacity inside the energy sector. For energy systems relational analysis requires the integration of two non-equivalent representations: (i) the functional view identifying and describing the relations that functional elements have among themselves and with the whole to which they belong; (ii) the structural view identifying and describing the relations between functional elements and structural elements within a given spatial context (González-López & Giampietro, 2017).

Four functional components can be distinguished in the oil and gas sector that jointly fulfill its expected role: the extraction system, the transportation system, the refinery system, and the final distribution. To express their expected function, each of these functional components is made up of structural elements (Figure II-1).

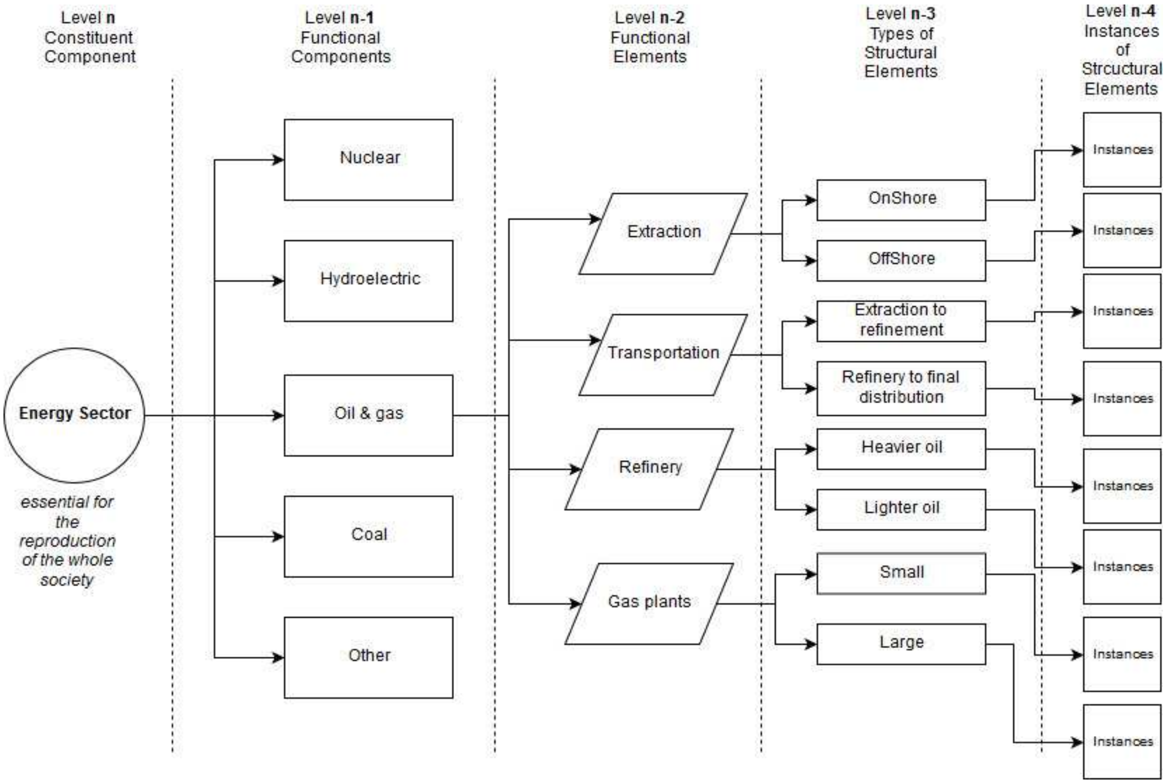


Figure II-1 The relation over the distinct categories used to organize the quantitative characterization of the performance of the oil and gas sector.

Within this framework the metabolic pattern expressed by the gas and oil sector can be described as a sequential pathway generated by the different functional elements (e.g., extraction, refining, transportation), each of which is made up of different structural elements (e.g. plants adopting different extraction techniques, diverse types of refineries, different methods of transportation) located in space.

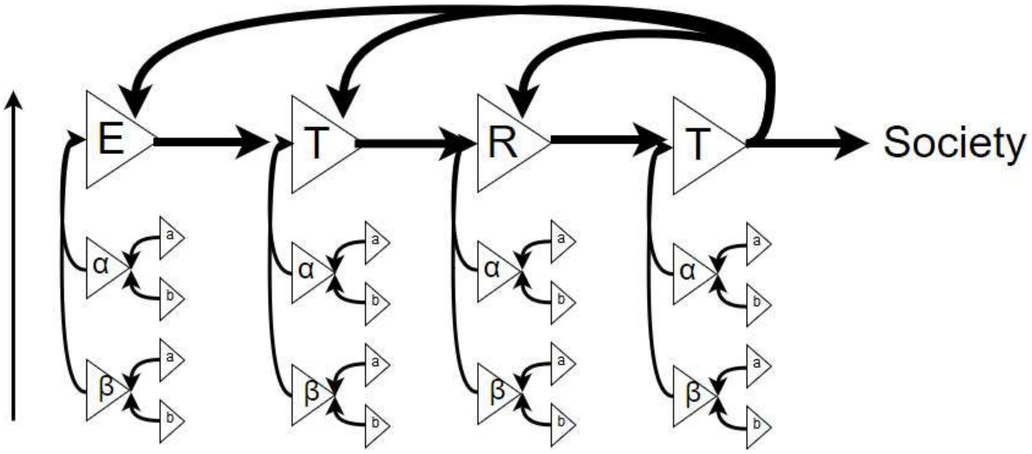


Figure II-2 Structure and scaling of the oil & gas sector pathway. As described in the figure, the pathway is interlinked between the different nodes.

E=Extraction, T=Transport from extraction to refinery or transport from refinement to consumption, R=Refinement. The pathway is scaled up from the structural elements (a, b) that conform the different functional nodes (a, β).

Note that the sequential metabolic pattern in the functional view (extraction → transport → refining) is not linear when considering the flows over structural elements in the structural view. Realizations (instances) of structural types are always associated with a location in space. For instance, specific refineries are in specific regions. Therefore, depending on the geographic location of the structural elements operating in the oil and gas sector, the organization of the expression of the various functions can be done in diverse ways. In fact, in Mexico, the operations of the gas and oil sector are realized through several different combinations of functional and structural types (a functional type of refinery linked to a structural type of refinery, Figure II-2). This is important for the scaling up of the different processes resulting in the whole metabolic pattern.

Functional elements

Each of the functional parts is described using "processors", which are sets of data arrays that contain information about the profile of inputs (production factors, including resources under human control and resources from the environment) and outputs (the specific product as well as the pollution product of the studied process) associated with the process. For example, what is the function of the refineries that process heavy oil versus that of the refineries that process light oil, while in the structural part we can see in a synthesized way what is the difference in performance between two different instances.

It is important to differentiate between these two elements as many analyses only focus on one of them, losing information about the why, the what, the how and where the system works.

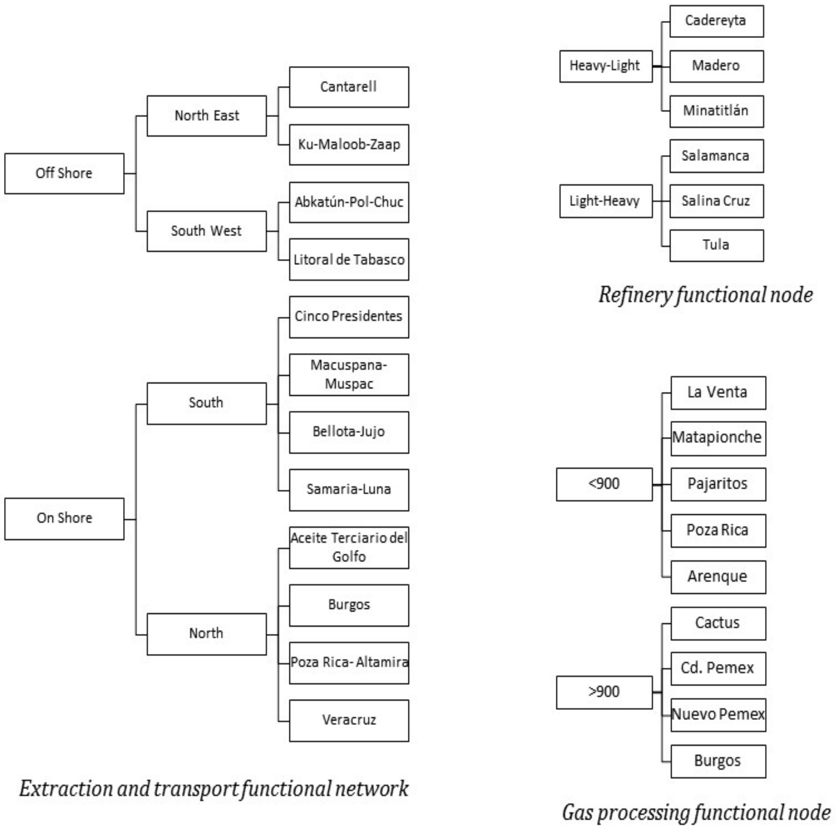
Structural elements

Structural elements describe the performance and the location of each instance of the system. The metabolic characteristics of these nodes are described both in extensive and intensive terms. On the one hand, the extensive variables are measured in a conventional way without scaling per unit of throughput or per unit of fund element. Intensive variables, on the other hand, are measured by scaling a flow by a unit of throughput or by a unit of fund element. The intensive variables permit to compare inside nodes or across nodes because they are scaled by the same unit. For example, a way to compare between refineries would be by comparing the amount of energy used per unit of oil processed. Or in the case of comparing across nodes, it would be the amount of energy employed or emissions generated per unit of oil processed, extracted or transported.

Data sources and organization

Most of the data presented here were obtained from PEMEX (Mexican Oil State Company) through use of the National Transparency System of Mexico (SNT), as the required data is not readily available in common databases. Other sources were the Institutional Database from PEMEX and the Energy Information System from SENER (Mexican Energy Secretariat).

The data was organized by structural and functional elements as shown in Figure II-3.



Extraction and transport functional network

Refinery functional node

Gas processing functional node

Figure II-3 Structural elements of the functional nodes' extraction and transport, refinery, and gas processing.

II.4 Results

Extraction

Mexico obtains most of its oil from offshore extraction, from the North-East region where most of the heavy oil is extracted, most of the CO2 is emitted by gas flaring and most of the energy for extraction is employed in absolute terms (Figure II-4 and Figure II-5, and Table II-1). The South-West region seconds the North-East in extraction terms. In this region, most of the Mexican light and superlight oil is extracted. The third producer region is the South. It produces the highest quantities of superlight oil in Mexico and demands the highest labor input. The North is the fourth oil-producing region. It has the second largest CO2 emission per unit of oil extracted, and the highest ratio of labor invested per energy extracted (Table II-1).

Most of the gas produced comes from onshore extraction, notably from the North region.

The South region has the highest ratio energy consumed per energy extracted but its ratio CO2 emission per energy produced is the second smallest. The North-East region has the highest ratio of CO2 emitted per energy extracted. The South-West region has the smallest ratio of CO2 per energy extracted.

In resume, the offshore regions produce more oil, in specific light and heavy, while the onshore regions produce more superlight oil and gas. Offshore extraction emits more CO2 to the atmosphere compared to onshore productions which have a bigger labor per energy and energy consumed per energy obtained ratios. Offshore areas have associated gas while in the onshore areas the non-associated gas increases. The amount of gas that is burned is greater in these areas than in onshore areas due to the poor performance in the separation of oil and gas. This has environmental and strategical consequences given that enormous amounts of gas are burned.

Onshore areas have more gas than oil, so they have another functional state in the system and different extraction tactics.

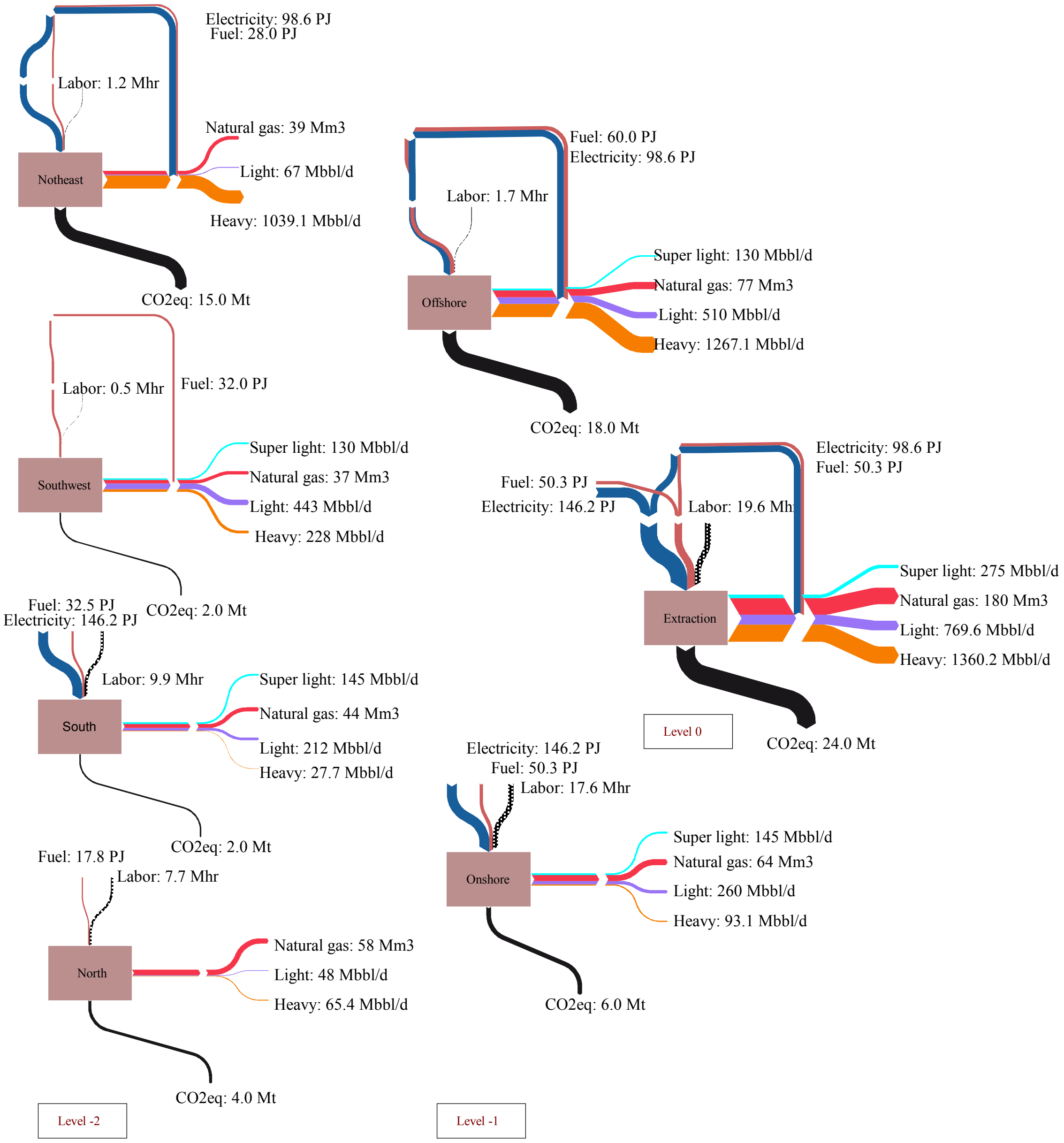


Figure II-4 Functional node showing the scaling of extraction regions.

Table II-1 Extraction system (Structural information).

Level 0 Extraction system				
Level -1 Extraction zones	**Offshore**		**Onshore**	
Level-2 Regions	**NE**	**SW**	**N**	**S**
Extensive variables				
Gross Energy Consumed (PJ)	126.58	32	17.82	178.66
Labor (Mhr)	1.2	0.48	7.7	9.9
CO_2 (t)	1.58×10^7	2.70×10^6	4.20×10^6	2.32×10^6
Gross Energy Extracted (PJ)	3059	1924	1046	1482
Intensive variables				
Labor/Gross Energy Extracted (10^3 hr/PJ)	0.4	0.2	0.7	0.7
CO_2/Gross Energy Extracted (t/PJ)	5.15×10^3	1.40×10^3	4.01×10^3	1.57×10^3
Gross Energy consumed/Gross Energy extracted (PJ/PJ)	0.04	0.02	0.02	0.12
Quality of the Energy consumed				
% Fuel	22%	100%	100%	18%
% Electricity	88%	0%	0%	82%
Source of electricity	Self-generated			grid

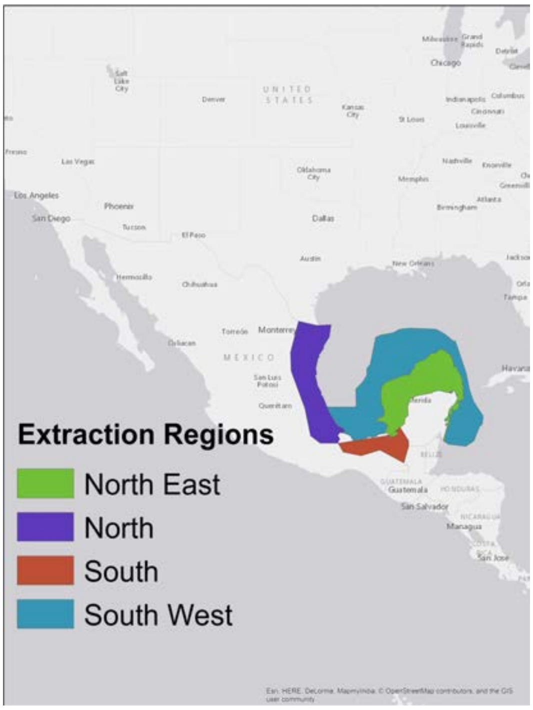


Figure II-5 Regional division of oil and gas extraction systems.

Refining

The definition of functional nodes in the refinery sector is based on whether they process predominantly heavy or light oil as the relative technologies employed require distinct types of fuel for processing. Refineries that process predominantly heavy oil requires more dry gas and natural gas for processing. Refineries that process lighter than heavy oil use more heavy oil, pet coke, and steam. Note that the output of the refinery system not only consists of energy but also other products destined for the building and manufacturing sector, the agricultural sector and the chemical industry (Figure II-6 and Figure II-10).

Refineries that predominantly process heavier oil require more energy inputs and labor and emit more CO2 to the atmosphere compared to refineries that predominantly refine light oil (Table II-2). Refineries processing lighter oil produce most of the electricity required by cogeneration. In many cases, the surplus is sent to the grid.

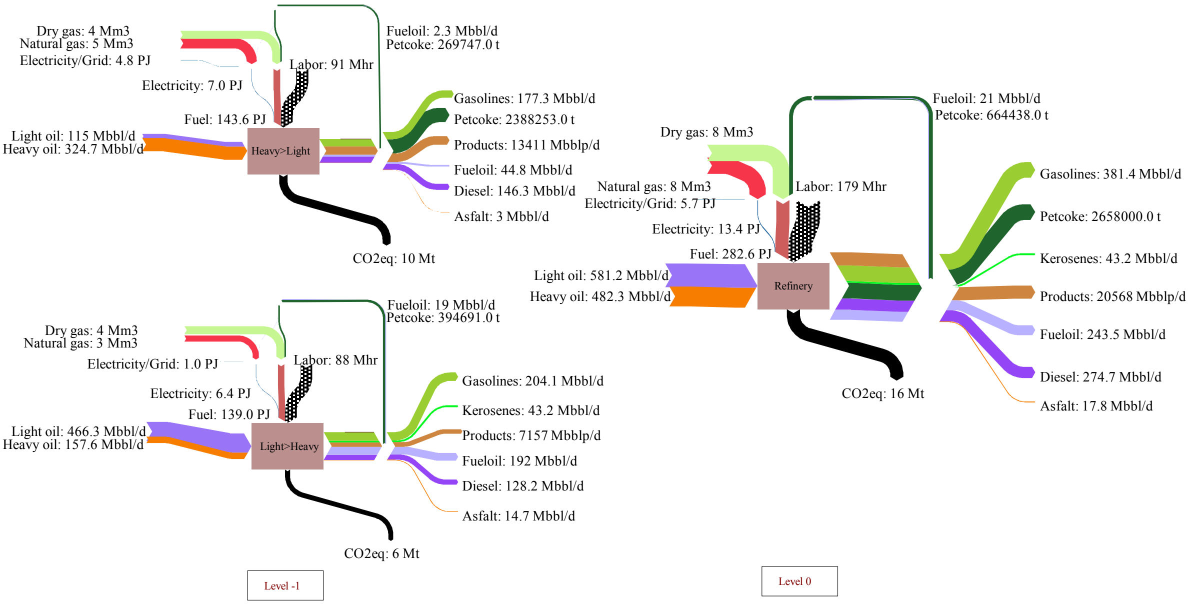


Figure II-6 Functional description of the refinery system, including quality and quantity of energy inputs, labor input, and energy and non-energetic outputs.

Table II-2 Refinery system (structural information).

Level 0 Refinery system		
Level -1 Refineries	>heavy	>light
Extensive variables		
Gross Energy Consumed (PJ)	151	145
Labor (Mhr)	91	88
CO2 (t)	$1.04\text{x}10^7$	$6.11\text{x}10^6$
Gross Energy Processed (PJ)	1675	1987
Intensive variables		
Labor/Gross Energy processed (10^3 hr /PJ)	54	44
CO2/Gross Energy processed (t/PJ)	$6.19\text{x}10^3$	$3.08\text{x}10^3$
Gross Energy consumed/Gross Energy processed (PJ/PJ)	0.09	0.07
Quality of the Energy consumed		
% Fuel	95%	96%
% Electricity	5%	4%
Source of electricity	Grid	Self-generated
Power capacity		
Power capacity (MMbd)	750	890
% Utilization factor	59%	70%

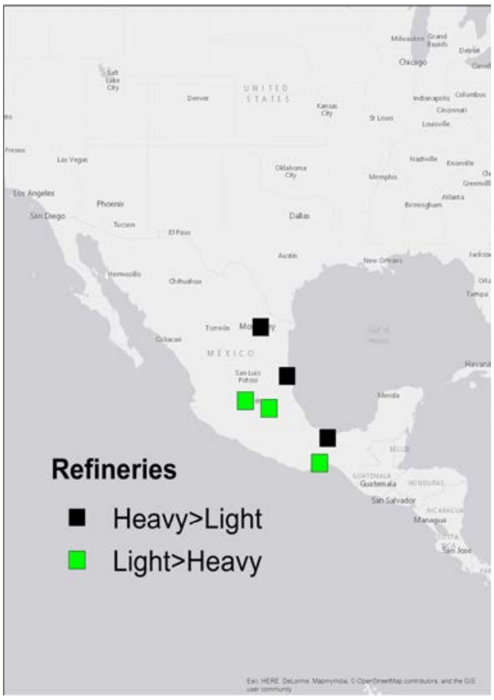


Figure II-7 Refinery system (Spatial structural information).

Refineries predominantly processing heavy oil operate at 59% of their capacity (utilization factor 0.59); those that process predominantly light oil at 70% (Table II-2).

Gas processing

The energy carriers obtained in gas processing are gasoline, ethane, gas LP and dry gas. Small gas processing plants produce proportionally more ethane than the bigger gas processing plants (Figure II-8). Larger gas plants require less labor per energy processed than smaller plants but consume more energy and generate more CO2 per energy processed than smaller plants (Figure II-9).

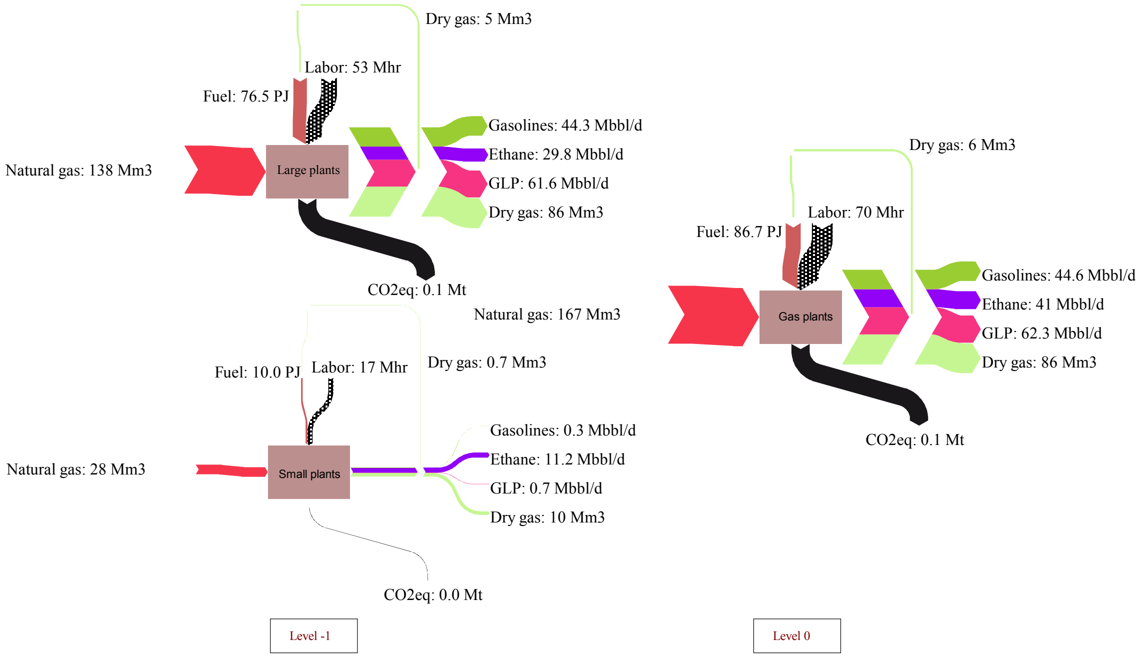


Figure II-8 Functional description and scaling of the gas processing system including the quality of the energy inputs and energy and non-energetic outputs.

Table II-3 Gas processing plants (structural information).

Level 0 Gas processing system		
Level-1 Gas plants	**>25x10^6 m^3**	**<25x10^6 m^3**
Extensive variables		
Gross Energy Consumed (PJ)	77	10
Labor (Mhr)	53	17
CO_2 (t)	8.79x10^4	1.38x10^3
Gross Energy processed (PJ)	1883	394
Intensive variables		
Labor/Gross Energy processed (10^3 hr/PJ)	28	43
CO_2/Gross Energy processed (t/PJ)	47	4
Gross Energy consumed/Gross Energy processed (PJ/PJ)	0.04	0.03
Quality of the Energy consumed		
% Fuel	100%	100%
Power capacity		
Power capacity	138x10^6 m^3	34x10^6 m^3
% Utilization factor	69%	59%

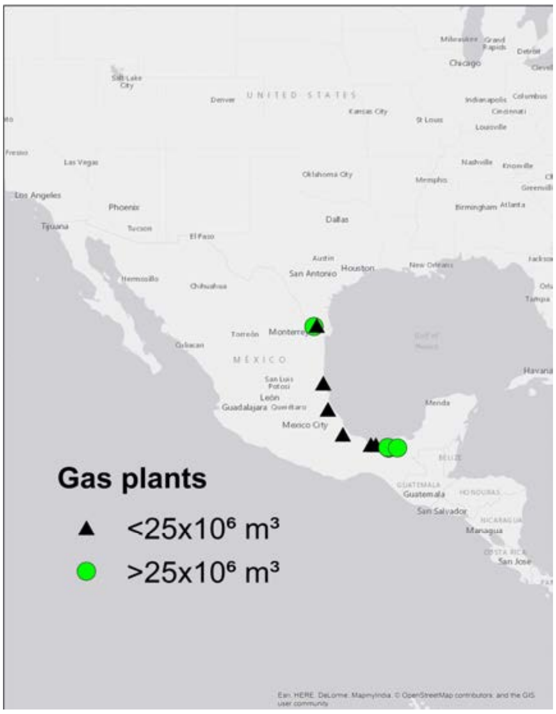


Figure II-9 Gas processing system (Spatial structural information).

The bigger gas processing plants operate at 69% of their capacity utilization, the small processing plants at 59% (Table II-3).

Transport

Transport from extraction regions to refineries and gas processing plants

Transport in offshore regions emits more CO2 in both extensive and intensive terms. The North-East region demands more labor in absolute terms, but in terms of labor input per unit of energy processed the onshore regions are most demanding. The North region spends half of its energy in transport. This is to be expected given the huge area of this region (Table II-4).

Transport from refineries and gas processing plants to final consumption

60% of the oil and gas products are transported by pipelines, 36 percent is transported by boats, and the rest by terrestrial transport (in this analysis terrestrial transport is omitted given the small number of products transported this way 4%). Pipelines are less labor demanding but are more energy intensive and emission intensive than ships (Table II-5).

Table II-4 Transport system 1 (Structural information).

Level 0 Transport from extraction to processing				
Level -1 Extraction zones	**Offshore**		**Onshore**	
Level -2 Regions	**NE**	**SW**	**N**	**S**
Extensive variables				
Gross Energy Consumed (PJ)	28	5	25	0.23
Labor (Mhr)	2	1	2	2
CO_2 (t)	1.76x10^{6}	9.40x10^{5}	6.32x10^{2}	4.90x10^{1}
Gross Energy Transported (PJ)	3014	2008	1046	1463
Intensive variables				
Labor/Gross Energy Extracted (10^{3} hr/PJ)	1	0.3	2	1
CO_2/Gross Energy Extracted (t/PJ)	585	468	1	0
Gross Energy consumed/Gross Energy extracted (PJ/PJ)	0.01	0	0.02	0.0002
Quality of the Energy consumed				
% Fuel	100%	100%	100%	100%

Table II-5 Transport system 2 (Structural information).

Level 0 Transport from processing to consumption		
Level -1 Technology	**ships**	**pipelines**
Extensive variables		
Gross Energy Consumed (PJ)	73x10^{-5}	12
Labor (Mhr)	12	0
CO_2 (t)	2.62x10^{5}	8.24x10^{5}
Gross Energy transported (PJ)	1281	2197
Intensive variables		
Labor/Gross Energy transported (10^{3} hr /PJ)	0.0093	0
CO_2/Gross Energy transported (t/PJ)	204	375
Gross Energy consumed/Gross Energy transported (PJ/PJ)	57x10^{-8}	53x10^{-4}
Quality of the Energy consumed		
% Fuel	100%	100%

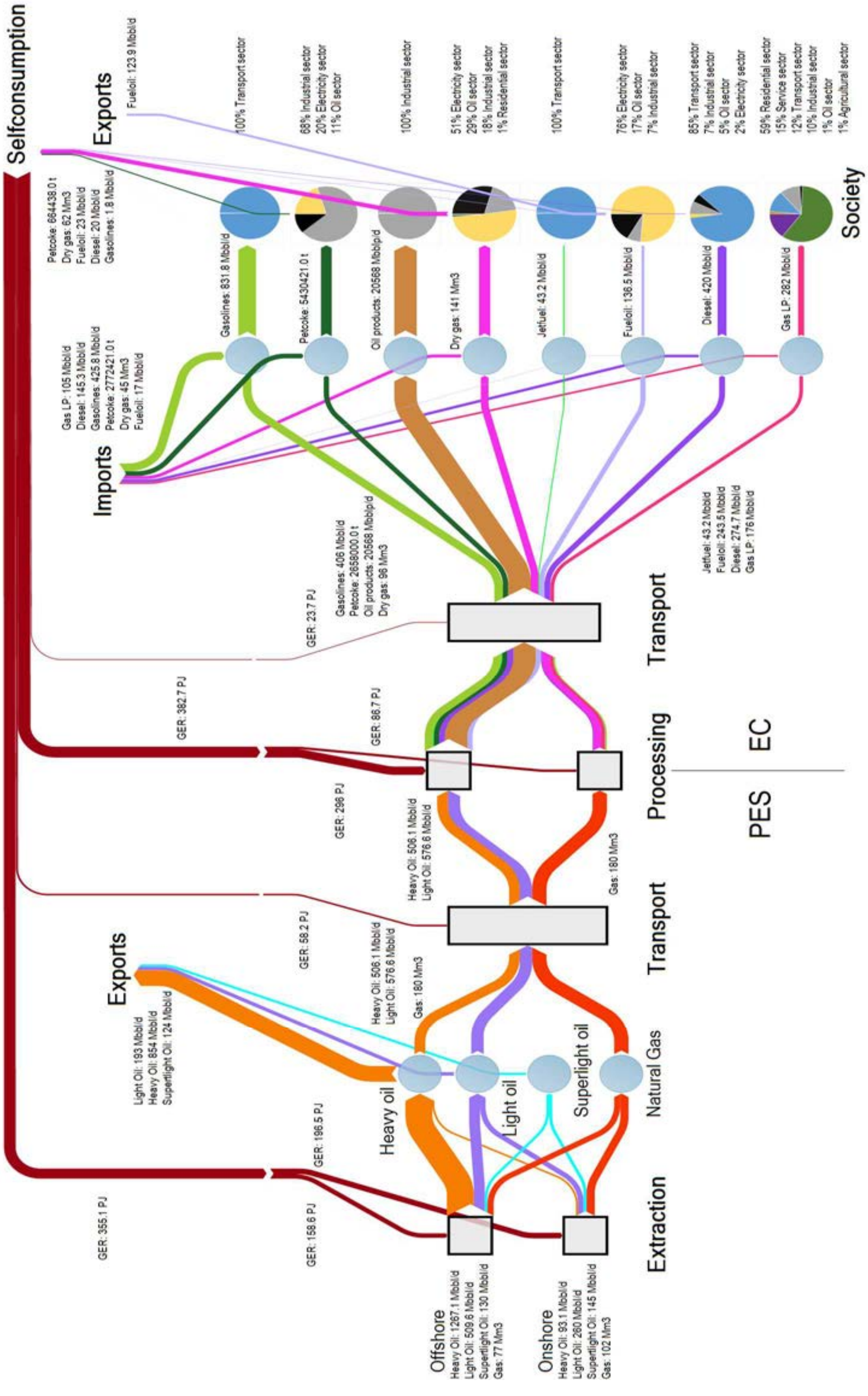


Figure II-10 The complex metabolic pathway described in terms of functional elements.

The different flows are transformed across the metabolic pathway from Primary Energy Sources (PES) extracted from the different reservoirs to Energy Carriers (EC) delivered to society.

Performance of the oil and gas sector as a whole

In this section, the information describing the various functional elements of the system is combined to analyze the overall performance of the oil and gas sector in relation to both its functional components and its overall characteristics. Indeed, the oil and gas sector is a constituent component of society and its metabolic pattern must stabilize a complex network of pathways: the set of inputs used by the oil and gas sector and the set of outputs delivered to the rest of society. This is illustrated in Figure 16 for Mexico.

Analysis of the functional elements (across regions)

Considering the extensive variables (overall quantities per year), extraction is the most energy-consuming function, followed by refining, then gas processing and finally transportation (Figure II-12). Considering intensive variables (quantity of input per unit of output), the most energy-intensive system is refining, followed by extraction, gas processing, and transport from extraction system to processing. The least energy intensive system is transportation from processing to consumption.

About labor, in extensive terms, the functional element requiring more hours of work is refining, followed by gas processing, and extraction. Transport is the least demanding in this regard. In intensive terms, the same pattern is found, with refining being the most labor-intensive function and transport the least labor-intensive function.

Regarding emission, considering extensive variables the functional element that emits more CO_2 into the atmosphere is extraction, followed by refining, gas processing, and finally transport. Expectedly, this pattern is like that for energy demand. Transport from extraction to processing emits more CO_2 than transport from processing to end use. When using intensive variables, the most emission-intensive functional element is refining followed by extraction, then by the transport system and finally by the gas processing system.

Whole system indicators

An integrated set of indicators characterizing the overall performance of the oil and gas sector can be obtained by summing the extensive variables (the quantities of inputs and outputs used by the processors describing the different functional elements). An example is provided in Figure II-12. Note that the choice of these indicators can be done "a la carte" in relation to the specific policy problem considered now of developing the analysis. In fact, when adopting relational analysis there is an impredicative relation between the framing of the issue (what is the question) and the characterization of the system in the analysis (what the relevant functional and structural elements are and what are the relevant inputs and outputs to be included in the assessments).

Figure II-11 Representation of the entire system interconnected by the transport system.

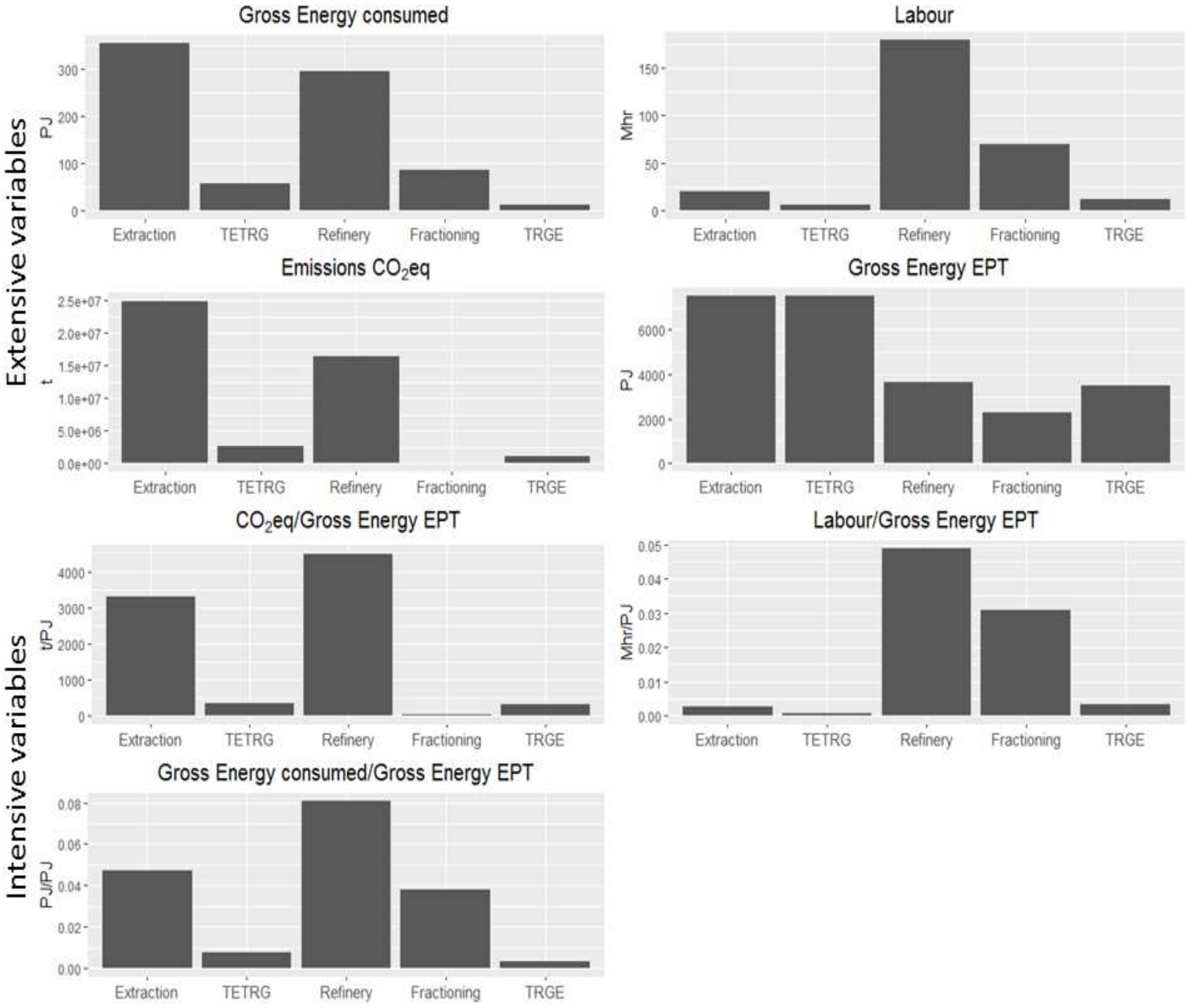


Figure II-12 Example of indicators characterizing the bioeconomic performance of the whole oil & gas sector.

TETRG=Transport from extraction to refineries and gas processing plants. TRGE=Transport from refineries and gas processing plants to end use. EPT= Energy extracted, processed or transported. Data refer to Mexico.

End-uses of the outputs of the oil and gas sector

Almost all the gasoline produced in the Mexican oil and gas sector is used in the transportation sector. Fuel oil is an undesired product (by-product) and within Mexico, it is used as input for electricity generation, which results in massive amounts of CO_2 emitted into the atmosphere (Santoyo-Castelazo, Gujba, & Azapagic, 2011). Almost all the fuel oil comes from the refineries that process lighter mixes of oil, and specifically from the Salina Cruz refinery that has an old configuration (Rana, Sámano, Ancheyta, & Diaz, 2006). Fuel oil has less added value than other fuels such as gasoline and jet fuel, and as shown in the metabolic pathway half of the fuel oil produced is exported as such rather than being further processed into gasoline. Further processing of fuel oil would reduce the need for gasoline imports.

Gas is claimed to be the transition energy of the 21 first century (Smil, 2015). However, note that in the Mexican supply system gas is tightly linked to oil because part of the gas is obtained from the same fields as oil. This is particularly true for the offshore regions, where many of the infrastructures are the same for oil and gas extraction. Gas production cannot be uncoupled from oil in Mexico unless the fields from where the gas is extracted do not have oil associated or there is the possibility for independent processing and consumption.

Petcoke is majorly destined to the industrial sector (68%) and used to a lesser extent by the electricity sector (20%) and the oil sector (11%). Petrochemicals are used in their majority by the industrial sector as inputs for processing, varying from the cement industry, food, pharmaceutical, etc. Kerosene is demanded by the transport sector for airplanes. Fuel oil is demanded the most part by the electricity sector (Figure II-10), then by the industrial sector, the oil sector and the electricity sector. Most of the gas LP ends up in the residential sector, seconded by the service sector, then by the transport sector, the industrial sector, the oil sector, and the agricultural sector.

Imports and exports

Fifty percent of the gasoline is imported (Figure II-10). Two-thirds of the heavy oil is exported, almost all the superlight oil is exported, and one-fifth of the light oil is exported. Half of the dry gas is imported, one-third of diesel is imported, and one-third of LP gas is imported.

II.5 Discussion

It is impossible to check and study the performance of the oil and gas sector by using simple systems of monitoring and control in the form of input/output indices or simple ratios of investment that mix information of different qualities. An analytical tool kit informing policy must have an adequate power of discrimination to find relevant characteristics across different scales and different dimensions of analysis. This requirement of variety in the analysis has been neatly summarized in Ashby's law of requisite variety (Ashby, 1956) and was well known to the pioneers of energetics in the 70's. When dealing with the analysis of complex energy systems one has to diversify the accounting of different energy forms associated with different processes carried out in the metabolic pathway in different places and at different times in relation to different types of inputs and outputs generated (IFIAS, 1978; Leach, 1975; Maddox, 1978). An effective energy analysis has to define an integrated set of indicators of performance and not just maximize input/output ratios applying naive definitions of efficiency (Smil, 2008a).

The creation of a richer information space to characterize the performance of the energy sector, as proposed in this paper, guarantees that the process of decision making can be better informed. Indeed, the proposed approach allows an assessment of changes taking place in the different structural and functional elements of the oil and gas sector in relation to employment (labor), bio-economic costs, technical issues, regional development, and environmental impacts. Changes in lower-level components can be scaled-up to changes in the overall performance of the whole sector. Therefore, this type of analysis can anticipate trade-offs in policy discussions, such as the pros and cons of (i) exporting oil; (ii) producing and consuming oil domestically to support the different sectors of the economy; (iii) reducing emissions and environmental impact. The environmental implications (GHG emissions) of the exploitation of oil increasingly difficult to extract are particularly relevant in view of negotiating climate policies.

Mexico is currently modernizing its refinery system, incorporating electricity cogeneration and opening the system for new refineries. The information used to describe the performance of the energy sector should be able to inform a holistic discussion of the "whys" and the "how's" of this modernization. That is, Mexico should decide, based on a sound discussion, how to wisely use its finite resources of oil and gas in face of the trade-offs listed above. Can we characterize how the use of these resources is supporting the Mexican economy? What mix of products should be produced and consumed internally to support the development of the different sectors of the economy?

The dependency on importation is another factor essential for a discussion of the plan of modernization of refineries in Mexico. They, now, not only do not produce the gasoline required by the economy but also are not operating at their highest utilization factor. A similar problem is seen for gas processing plants.

When dealing with this type of problems, relational analysis of the metabolic pattern of society helps to establish a relation between the specific patterns of production (supply) of energy carriers (presented in this paper) and the specific patterns of end use in society. An energy end-use matrix uses the same logical approach to identify which type of energy products are used by the different sectors of the economy, how much, how and why (Giampietro, Velasco-Fernández, & Ripa, 2017; Velasco-Fernández, Giampietro, & Bukkens, 2018). In future work, I will use the same approach to analyze the metabolic pattern on the consumption side: to identify which sectors and subsectors of the Mexican economy are using which type of energy products to do what. Indeed, to improve the performance of the economy in the relation of the use of energy carriers, it is necessary to generate a holistic vision of the complete process of production and use of energy carriers in society.

Regarding the possibility of identifying and characterizing the nature of specific problems associated with geographic location, most of Mexico's oil reserves are in the North-East off-shore region, which is the most emission-intensive region. Using the integrated analysis presented here it is possible to look for solutions to the problem represented by the fact that the emissions are potential energy lost by the gas flaring. This influences also the refinery systems as it determines the mix of oil that can be processed. Much of the gas flaring is due to the gas associated with oil, which must be burned to reduce the methane emissions. One possible transition away from the existing situation, without major changes in infrastructures, would be the generation of dry gas: it emits less, and it demands less energy than the refinery system. Perhaps some fuels can be replaced by dry gas in the industry. The analysis of possible scenarios would be more robust if it could be checked in terms of relational analysis.

II.6 Conclusion

The relational analysis presented in this paper makes it possible to describe the bioeconomic performance of the oil and gas sector across different levels and dimensions of analysis. It establishes an analytical interface between the way (how) energy carriers are produced and how they are consumed in an economy. The resulting information space permits a holistic analysis of the energy and climate policies in relation to different objectives and provides a variety of indicators useful for different purposes. A holistic vision of the complex interplay between energy supply and demand-side is currently missing both in terms of policy and scientific analysis (Allen, Tainter, & Hoekstra, 2012; Arodudu, Helming, Wiggering, & Voinov, 2017). The approach can equally well be applied to renewables.

About the case of Mexico, the analysis shows that the direction of the Mexican Energy Reform is closely tied to the final cause of the oil and gas sector. Mexico should rethink the strategy of how to use its finite fossil energy resources and not only invest efforts in extracting more oil and gas and, in doing so, remaining stuck in business as usual. Given the volatility of the oil & gas prices, Mexico should reconsider oil export and instead employ this resource in activities that generate more added value and create less dependence on the oil market.

Qualitative reforms are recommended in final consumption and in the oil and gas system itself. A reform in the refinery system could address the current dependency on gasoline imports and generate fuels with more added value than that of the residual fuel oil that is currently employed for electricity generation and resulting in excessive amounts of emissions. A reform in the transport sector diversifying the fuels employed would help reduce the demand for imported gasoline. The incorporation of diversified sources of electricity generation that include renewables would reduce the amount of fuel oil and natural gas employed and by this reduce the emissions generated by the fuel oil consumption and the dependency on natural gas importation.

Mexico should incorporate the PostCOP agenda into the Energy reform, given that PEMEX is at the top ten fossil fuel producer's emitters in the world, and that many of the emissions are simply due to inefficacy in some of the offshore extraction regions where the gas associated with the oil extracted is flared and where most of the heavy oil reserves are allocated.

Chapter III Electricity metabolism[4]

III.1 Abstract

The efforts for a quick and radical decarbonization of the economies of a globalized world dramatically increase the complexity of solutions. In fact, it is not sure that we can fully predict the implications of quick and radical decarbonization for the stability of existing social-ecological systems. An application of the integration of Relational Analysis, developed by Rosen, and MuSIASEM is presented here to explore this issue. As a practical example, I consider the challenge of decarbonization in the electricity sector in Mexico. The analysis acknowledges the distinct functions of electricity production: intermittents, base-loaders with high adaptability, base-loaders with low adaptability, and peakers. This integration of different functions has to provide adaptability to the metabolism of electricity, within the interaction of society and the environment. The results show that, when considering the existing technological option space, decarbonization will entail an increase in land use by intermittent sources of energy and an increase in importations of natural gas. The increasing natural gas consumption may generate a rebound effect frustrating decarbonization efforts in long terms. This fact suggests that an alternative strategy of decarbonization should be based on a better harmonization of pattern of consumption and supply. Trying to change the behavior of one of the two sides at the time (consumption and supply) will not bring any substantial solution. Since the functional characteristics of the different electricity sources are affected by many different constraints, information useful for policy discussion, should be capable to characterize how the various constraints associated with different energy sources (the mix of types of power plants) translate into a set of constraints over the expression of the resulting function (electricity supply).

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[4] This chapter builds on the accepted paper for presentation at the 4th International Conference on Energy and Environment: bringing together Engineering and Economics. Guimaraes, Portugal, May 16-17, 2019.

III.2Introduction

The complexity of energy issues is becoming higher, and with this, we are facing dilemmas or trilemmas (Labanca, 2017; World Energy Council, 2013), Figure III-1. The mainstream idea when dealing with the conversion to alternative electricity production is to maintain or increase the amount of energy produced while respecting the environmental boundaries of our planet. However, this may result a mission impossible. The decarbonization efforts in electricity production can be used as an example after combining the goals of: (i) reducing the amounts of CO_2; (ii) guarantee energy sovereignty; and (iii) keeping (or expanding) the actual energy levels of production. The feasibility of this result depends on the severity of biophysical constraints (e.g. land requirement). The viability of this result depends on the ability of tackling the challenge represented by the properties of electricity (an energy form that has to be produced and consumed simultaneously and difficult to store) when produced with unreliable and intermittent sources. The desirability of this result depends on the requirement imposed by societal end uses of electricity.

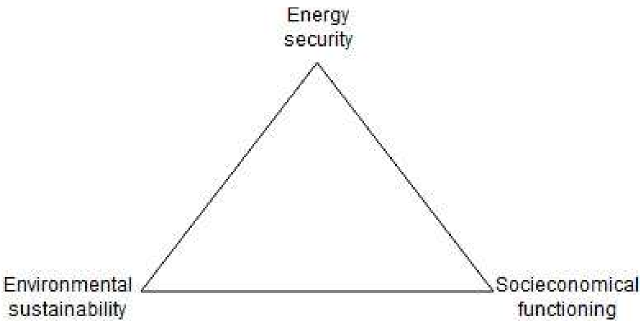

Figure III-1 Exemplification of a common trilemma in energy analysis.

With the industrial revolution the energy sector (and the rest of society) enjoyed a temporary emancipation from land due to the power density properties of fossil fuels (Mayumi, 1991). However, by replacing the fossil fuels with renewables, we will return to a situation in which the availability of land can return to be a constraint. In this new (old!) situation the requirement of land to produce energy carriers can entail a competition for the use of land with other societal and economic functions (Scheidel and Sorman, 2011).

In this sense, a relational analysis of electricity production in Mexico represents an interesting case study, given the political importance of the subject and the international role that Mexico has in climate change negotiations. The state-owned Federal Electricity Commission (CFE), the 6th power company in the world, has opened the production to the market. At the same time, Mexico is among the top ten oil producers in the world (Alpizar-Castro and Rodriguez-Monroy, 2016). Due to this availability a great part of domestic production of electricity is based on this resource. However, at the same time, Mexico is importing half of the natural gas to produce electricity from the USA. To understand this fact, we have to use the distinction proposed between base-loaders that can use various fossil energy sources and peakers based on natural gas.

The goal to increase up to 30% the share of renewable electricity from the total share is associated with the plans from the Energy Secretariat to reduce the emissions to 30% for 2020 and 50% to 2050. At the moment these objectives seem to be difficult to fulfill as the interactions among relevant actors and the interactions of renewable sources with non-renewable sources represent a very complex system difficult to control and predict (Jano-Ito, et al., 2016).

III.3Constituent components

In this case it is difficult to reduce the analysis of the electric sector of Mexico to the description of the existing constituent components. As Cilliers wrote in the book *Complexity and postmodernism: Understanding complex systems* that: “Complex systems have to grapple with a changing environment. Depending on the severity of these changes, great demands can be made on the resources of the system. To cope with these demands the system must have two capabilities: it must be able to store information concerning the environment for future use; it must be able to adapt its structure when necessary." This implies that in the actual fluid situation it is difficult to identify expected relations between functional and structural elements that can be assumed to remain constant in the future.

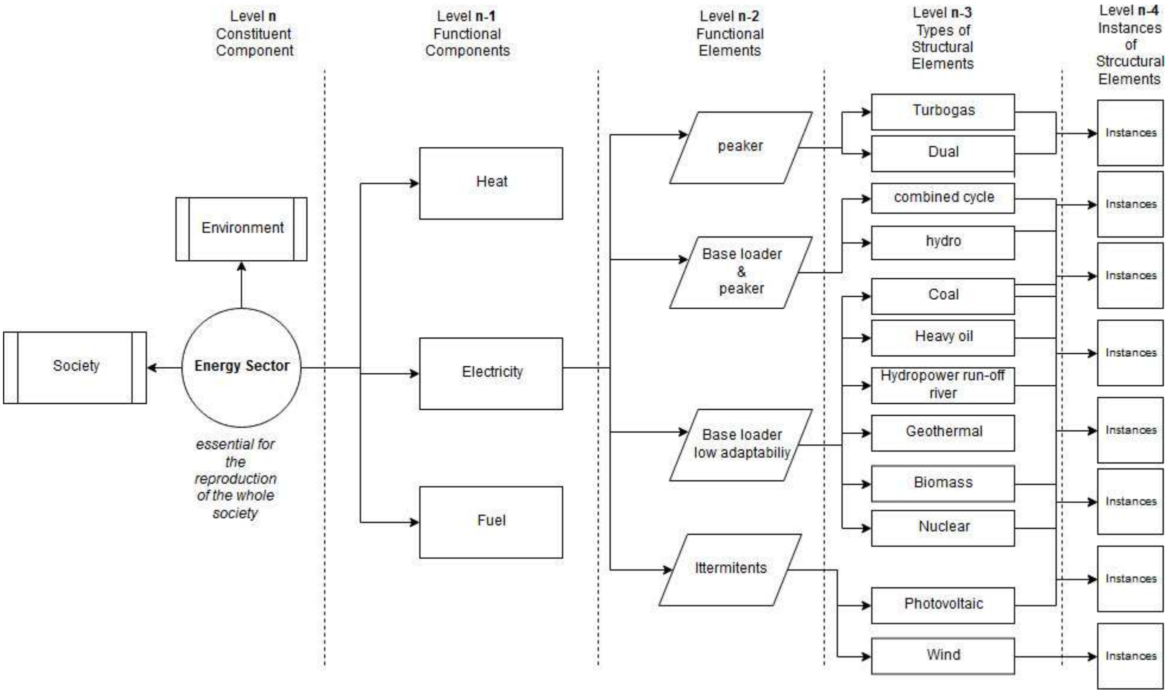

Figure III-2 Hierarchical organization across levels of electricity production in a social-ecological system.

Functional elements

They are elements useful for describing in quantitative terms the interaction between the environment and society and between the parts of the society. In relation to the production of electricity to be tailored on the characteristics of the demand we can define three functions for a power plant: (i) providing a predictable supply; (ii) providing a regulable supply; and (iii) reducing the cost of the supply. In relation to these functions Baseloaders are providing a predictable but not regulable supply which has a medium cost, whereas Peakers are those elements that can provide the two first functions, but with a higher cost. Finally, Intermittents cannot deliver in relation to the first two functions because they depend on unpredictable and uncontrollable environmental conditions, but they can produce electricity at low cost (when they produce). This narrative describe what the various typologies of power plants do in terms of their functional role in the electric sector.

Structural elements

Structural elements are the material entities which interact directly with the environment and society. Their behavior is associated with their structural organization. The operations of structural elements can be combined to generate emergent properties at a larger functional level – e.g. the combination of coal plant, gas turbine plant and wind mills in the electric sector. In brief, we can observe the structural elements to study how the electric system produce electricity. (as see in Figure III-2).

Data sources

Electricity information was gathered from the Energy Information System from SENER (Mexican Energy Secretariat). The information used to calculate emissions is from the articles Santoyo-Castelazo, Gujba, and Azapagic 2011b; Navarro-Pineda, Handler, and Sacramento-Rivero 2017; Amponsah et al. 2014. The information about land use is from Smil 2015; Scheidel and Sorman 2012.

III.4Results

Societal end use

The industrial sector employs most of the electricity (48%), seconded by the household (18%) and finally by the service sector (10%). Losses represent a great part (13%) in comparison with imports (1%) or exports (3%).

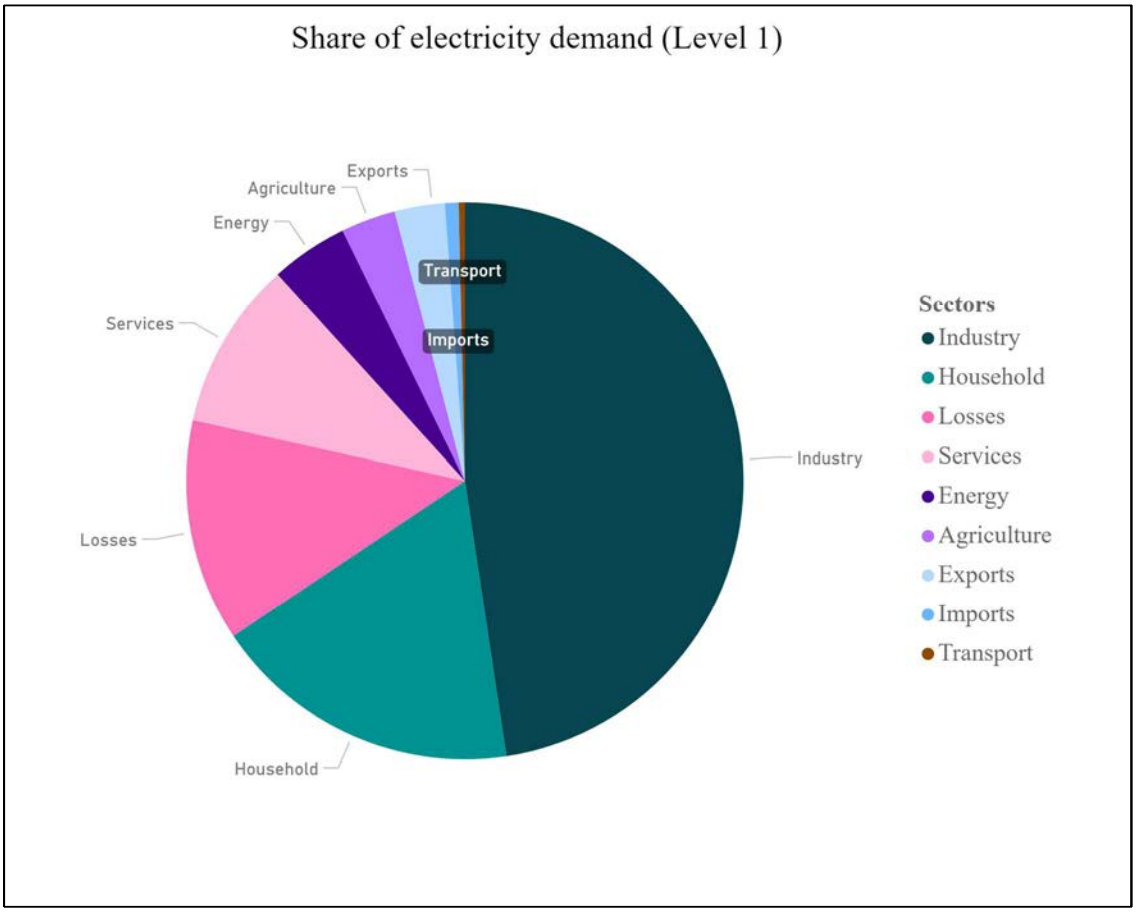

Figure III-3 Share of the electricity demand in Mexico.

The main source of demand in the industrial sector is the iron and steel industry. The chemical and the petrochemical industry second the industrial sector (Figure III-3). Apparently, the other industries don't have strong changes, but they're increasing their demand. The demand of other industries is stable, with a slight increasing trend.

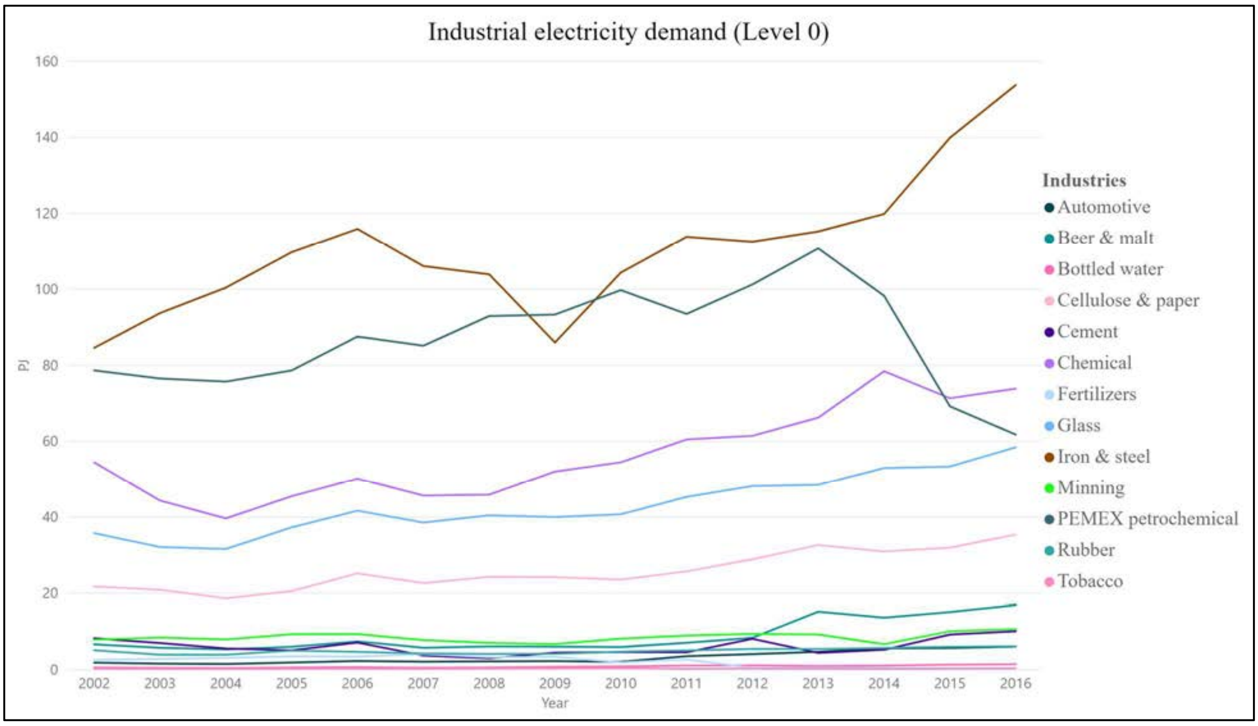

Figure III-4 Industrial electricity demand.

Electricity Metabolism

The main source of electricity generated comes from fossil fuel sources such as heavy oil, natural gas, and coal (Figure III-5). Seconded by hydroelectric sources. This means, that almost all the main sources are base load with peaker options (gas and hydro) and base load with low adaptability sources (coal and oil) - (Figure III-6). Intermittent sources play a negligible role in the current production matrix.

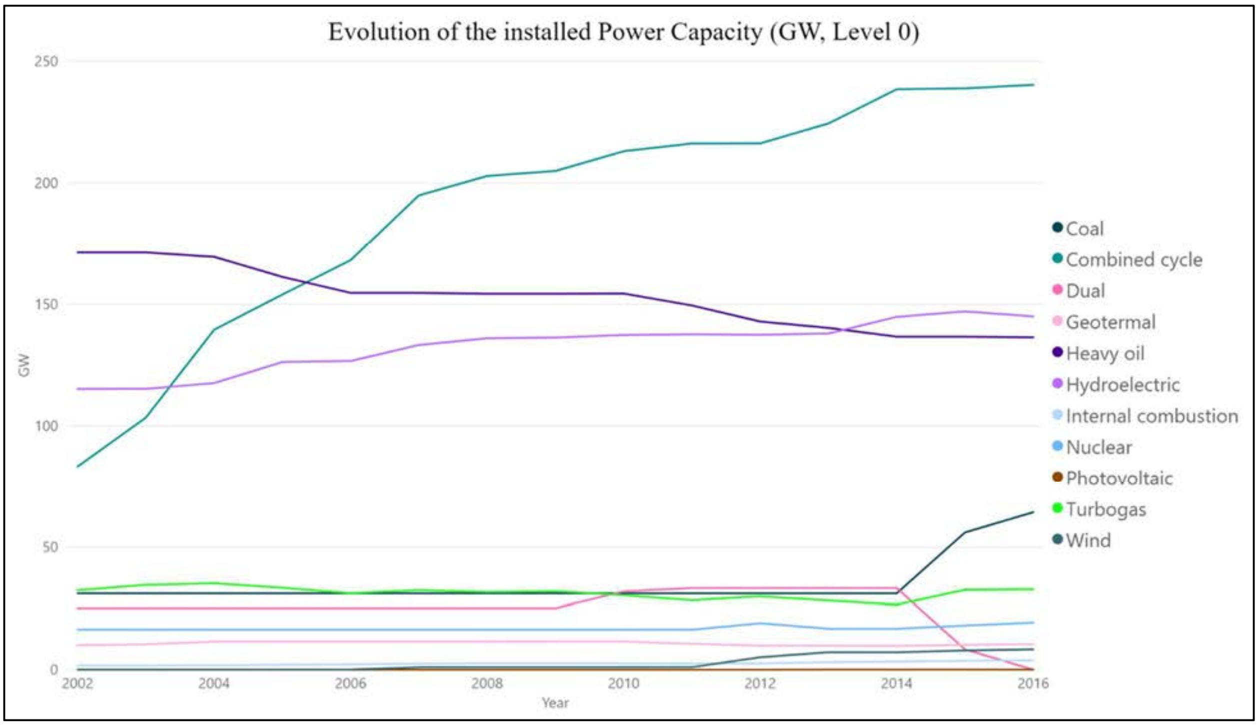

Figure III-5 Evolution of the power capacity installed per technology of electricity production.

According to Mexico's electricity production plans for 2030, the pattern will change (Table III-1). Intermittent sources are planned to substitute intensive emitter sources. Following this policy will, the wind is becoming the source with the highest increase in installed capacity seconded by combined cycle.

The combined cycle is the electricity source that has increased most in time (Figure III-5). Hydroelectric and combined cycle are the two highest installed capacities. However, the ranking of installed power capacity (MW) does not coincide with the ranking of quantities of electricity generated (GWh) due that the fact that the utilization factor in power plant using fossil sources is much higher (Table III-1).
The evolution of the proportion of the different installed capacities is illustrated in Figure III-6 : there's an increase in the base loaders with high adaptability. This is the main functional typology of power plant that is replacing the others. Intermittent (solar and wind) are less important in the total. Their penetration in the electric sector

seems not to displace other typologies of power plants. Intermittent power plants are just added to the other as illustrated in Figure III-6 and Figure III-7. On the contrary, *baseloaders* with high adaptability are displacing the most expensive *peakers* as electric sources.

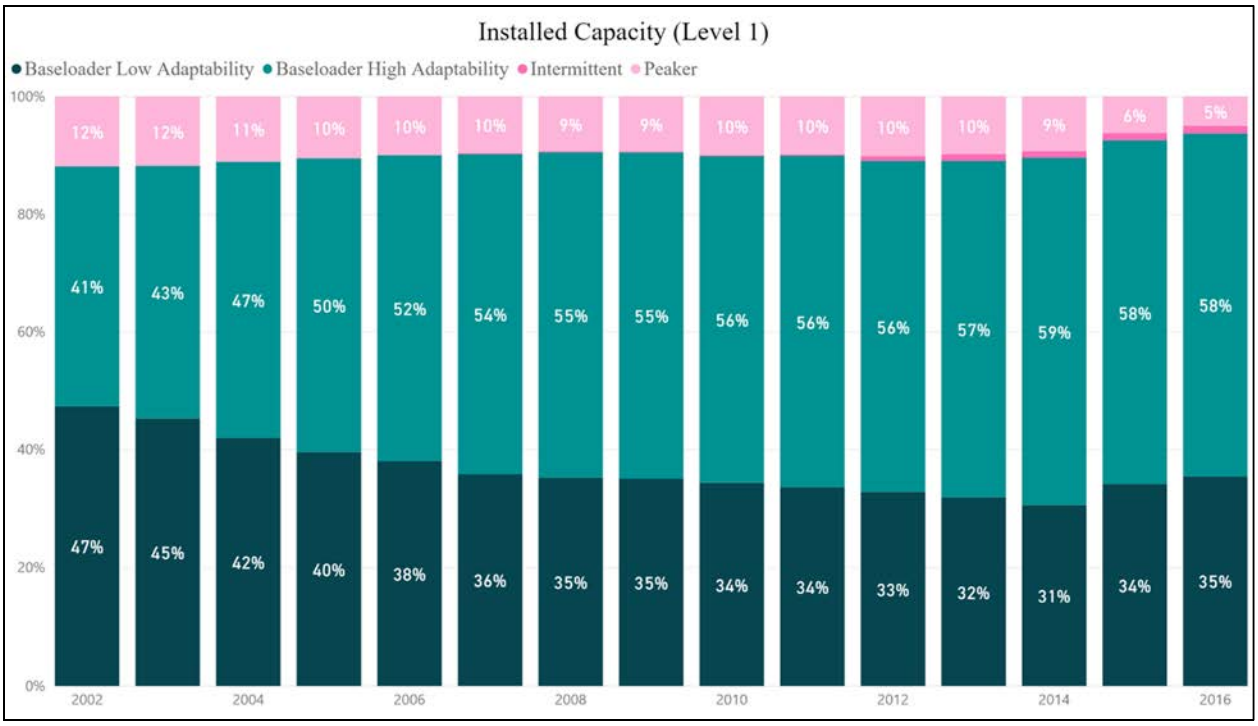

Figure III-6 Evolution of the proportion of the installed capacity at level 1.

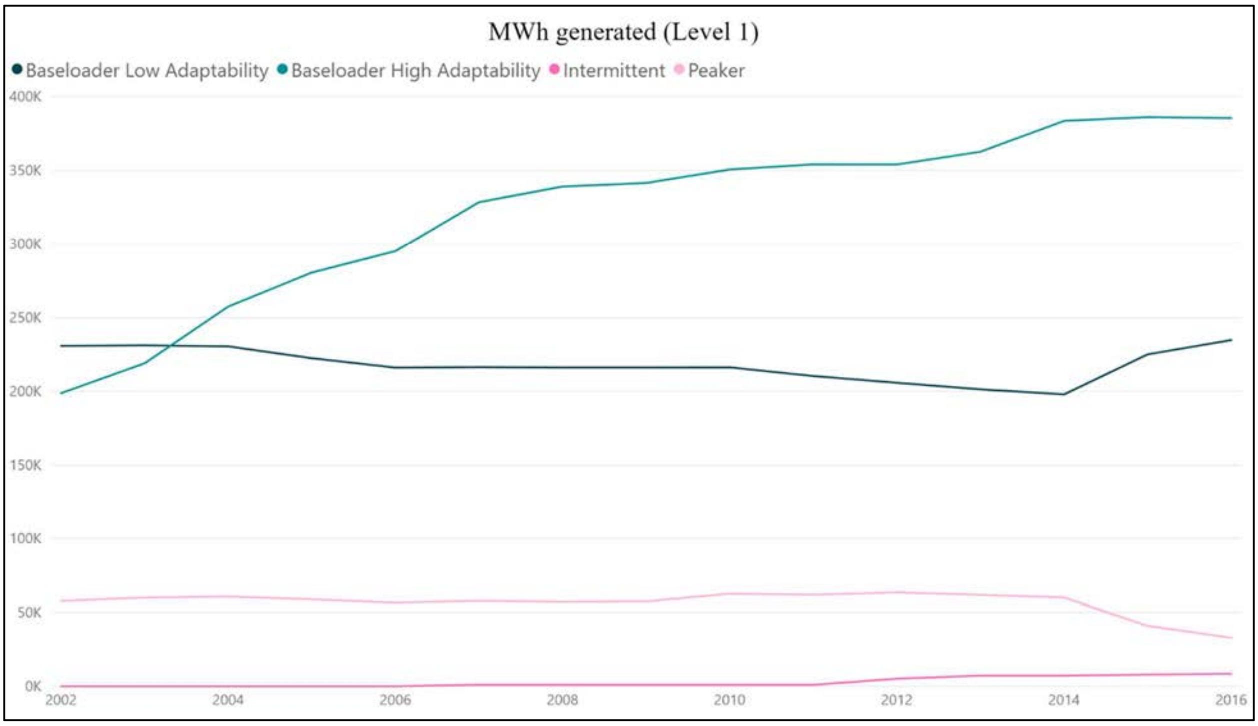

Figure III-7 MWh generated per source at level 1.

Table III-1 Comparison of the distinct functions, MWh generated, Utilization Factor, Installed Power Capacity and Prospective Power Capacity, Area required, emissions, carbon intensity and power density for the different Electricity production technologies.

Function	Technology	MWh generated	Utilization Factor %	Installed Power Capacity 2015 (MW)	Prospective Power Cacpacity 2030 (MW)	Area 2015 Km_2	Area 2030 Km_2	Emissions 2015 tCO_2eq	Emissions 2030 tCO_2eq	Emissions 2030 BAU tCO_2eq	tCO_2eq/MWh	Km_2/MWh
bla	Heavy oil	3.57E+07	36	1.14E+04	3.30E+02	2.28E+01	6.60E-01	3.20E+07	2.11E+06	5.19E+07	8.98E-01	6.39E-07
bla	Internal comb.	1.71E+06	65	3.01E+02	1.30E+02	6.03E-01	2.60E-01	1.38E+06	1.52E+05	2.24E+06	8.09E-01	3.53E-07
bla	Coal	3.01E+07	64	5.38E+03	1.20E+02	5.38E+00	1.20E-01	3.15E+07	1.48E+06	5.11E+07	1.05E+00	1.79E-07
bla	Nuclear	1.16E+07	88	1.51E+03	4.07E+03	3.78E-01	1.02E+00	1.27E+05	4.24E+05	2.06E+05	1.10E-02	3.26E-08
bla	Geotermal	6.29E+06	82	8.74E+02	1.62E+03	8.74E+00	1.62E+01	8.18E+05	1.62E+06	1.33E+06	1.30E-01	1.39E-06
bp	Combined cycle	1.34E+08	77	1.99E+04	2.64E+04	3.98E+01	5.29E+01	6.00E+07	1.15E+08	9.73E+07	4.46E-01	2.96E-07
bp	Hydroelectric	3.01E+07	29	1.20E+04	1.60E+04	2.00E+03	2.67E+03	1.20E+05	2.00E+05	1.95E+05	4.00E-03	6.67E-05
i	Wind	2.39E+06	39	6.99E+02	1.20E+04	2.33E+02	3.98E+03	4.06E+04	7.99E+05	6.58E+04	1.70E-02	9.76E-05
i	Photovoltaic	1.28E+04	24	6.00E+00	1.82E+03	5.45E-01	1.66E+02	3.83E+02	3.81E+05	6.21E+02	3.00E-02	4.28E-05
p	Turbogas	5.28E+06	22	2.74E+03	4.03E+02	5.48E+00	8.06E-01	2.36E+06	0.00E+00	3.82E+06	4.46E-01	1.04E-06
p	Dual	3.48E+06	19	2.10E+03	0.00E+00	4.20E+00	0.00E+00	3.64E+06	0.00E+00	5.89E+06	1.05E+00	1.21E-06
Total	Total	2.61E+08		5.70E+04	6.29E+04	2.33E+03	6.89E+03	1.32E+08	1.23E+08	2.14E+08	5.06E-01	8.91E-06

The resulting land use is expected to increase due to the low power density in alternative sources of electricity production. Land use demanded by the change in the pattern will exacerbate. Especially by the high increase in wind production (Table III-1). Emissions will reduce in comparison from 2015.

As shown in table 1, base loader options with low adaptability have a bigger utilization factor than peaker and intermittent sources. The base loader options with high adaptability have second the first described sources, except the wind source, which has the same utilization factor as these sources. As can be seen in table 1, there's a dilemma between land use and emissions. On the one hand, wind sources will reduce emissions considerably by replacing the installed capacity of intensive emitter sources, but they also will demand considerable amounts of land.

The external constraint on land use

The requirement of land use for the operation of the electric sector of Mexico is expected to increase due to the low power density in alternative sources of electricity production. Moreover, due to the low utilization factor, the land required for a massive move to wind production (Table III-1). will be significant. On the positive side, this move, if achieved, will significantly reduce emissions in comparison with the level in 2015.

The emissions can be reduced almost of a half of the business as usual scenario but this would require almost three times the current amount of land (Table III-1).

The problem with intermittent power generation

The poor functional performance of intermittent sources of electricity (their production is neither expected nor regulable) entails a systemic problem in their utilization. As illustrated in Figure III-8 the importation of natural gas in Mexico is surpassing national production. It is easy to predict that this pattern will increase in the future as a consequence of the policy of replacing intensive emission sources by intermittent sources. The more wind is used as source of electricity the more gas is required to back up the intermittency of this supply. This implies that as shown in Table III-1, if the deployment of intermittent source increase, also the emissions due to the use of natural gas will increase.

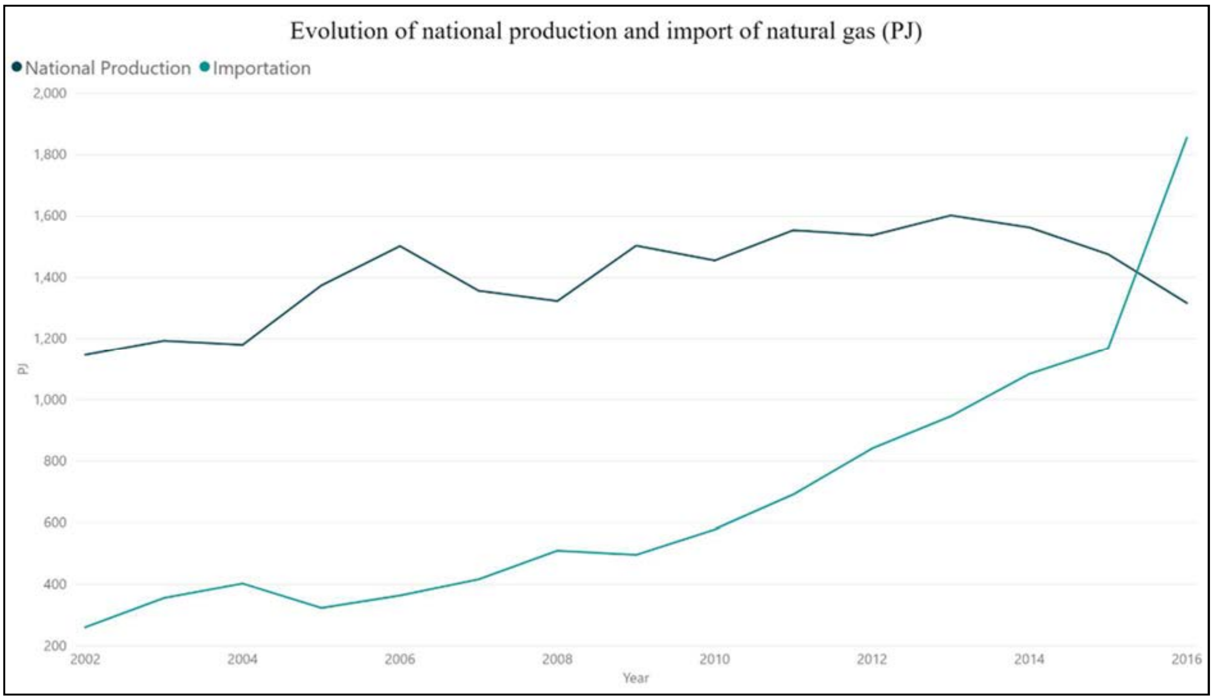

Figure III-8 Evolution of the production and importation of Natural Gas in Mexico.

III.5 Discussion

Mexican electricity consumption is different from the majority of other developed countries. The main source of electricity demand in Mexico is due to the activities of industrial sector, whereas, in the majority of other developed countries, the main source of demand of electricity is associated with the activities of the household and service sector.

The type of demand associated with the activities of the industrial sector is not compatible with the type of supply provided by non-intermittent sources of electricity. This translates into a skyrocketing demand of natural gas needed to make compatible the industrial demand with the intermittent supply, covering all the peaks missed by renewables (Smil, 2015). This fact explains: (i) the evolution of the installed capacity of combined cycle plants (increasing in Figure III-5)); and (ii) the importations of natural gas (Figure III-8), coinciding with the increase of the demand of electricity in the iron & steel industry.

As seen in Figure III-6 and Figure III-7, the current trends of changes in the electricity sector of Mexico seem not to what expected in the government plans.

This implies that either the transition to alternative electricity sources is more complex than expected (as discussed in the introduction), or the rhythm of the implementation is too slow. The main substitution in the Mexican electricity sector is made by the increase of base loaders with high adaptability such as the natural gas and not by intermittent sources.

Natural gas will still reduce the amounts of emissions per unit of electricity produced (Table III-1)by reducing coal and oil production. However, if the business as usual pattern remains the same, importations from natural gas will increase, and the emissions produced by its combustion will contrast the positive effects of wind power.

As a matter of fact, looking at Table III-1, the increasing consumption of natural gas will prevent a major reduction of emissions. If this pattern of substitution continuous we may experience a sort of rebound effect (Giampietro and Mayumi, 2018) on emissions, where more "efficient" solutions – i.e. intermittent generation of electricity - can lead to an increase of emissions because of the need of a back-up based on natural gas.

Again this apparent paradox illustrates the importance of analyzing in a holistic way the overall pattern of electricity production and consumption.

In the case of land, intermittent sources of electricity have lower power densities. According to the current plans, there will be an increase in land demand, particularly from the wind sources. This will lead to competition with other land uses necessary for other societal activities or for the preservation of natural habitats (Serrano-Tovar and Giampietro, 2013; Lomas and Giampietro, 2017).

The existence of these unavoidable trade-offs among different sustainability criteria flags the need for an integrated analysis of the metabolism of electricity across different dimensions and scales. It is time to question the functions of the production and consumption of electricity in economic, societal and environmental terms. Unfortunately, SENER plans seem to consider only changes in the current pattern of production of energy. The analysis should be much more holistic and address the possibility of changing the economic pattern together with the patterns of electricity production. More specifically, when looking at the future of Mexico, one should consider what will happen if Mexico will use electricity into other activities expressing a pattern of consumption different than the current one? The current pattern is mainly determined by the demand mainly of the industrial sector, but what if the growing service economy and the growing consumption of the households will change the existing picture?

Finally, we should always remember that there is another key aspect to be considered. The matching between the pattern of electricity production and the pattern of electricity consumption associated with to satisfaction of the different societal activities must be compatible with environmental constraints. As explained earlier, the integration in the electric grid of a large share of intermittent electricity may face important hurdles. Not only their behavior is unpredictable and non-linear, but also, they are affected by a geographic variability. This fact adds an additional complication to the analysis of the relation between installed power capacity, supply of electricity, environmental impact and constraints when considering the operation of a large electric grid operating without interruption during the year across large distances. This complexity makes the goal of reducing dramatically the emissions into the atmosphere even more difficult to achieve. For this reason it is essential that politicians and stakeholders do have access of an effective scientific information about the nature of the problems to be tackled avoiding dangerous simplifications in the analysis of the problems.

III.6 Conclusion

There is more need for analyses that integrate the relations between social-ecological systems and the environment across different dimensions and across different scales. Introducing the functional perspective on electric production/consumption, as done in this work, helps understanding some of these relations. The resulting information space elucidates how increasing the installed power capacity of less emission-intensive sources may not be as effective as expected if they are intermittent sources. Because of their low power density, they will increase the land demand of the electric sector. Because of their inability to fulfill neither the function of providing an expected electricity supply nor the function of providing a regulable electricity supply, they may entail unexpected side effects such as the increased reliance on natural gas. This entails a continuous loss of energy sovereignty when considering that half of this natural gas is imported.

Reforms in the metabolism of electricity in Mexico should address in a holistic analysis the implications of changes in the pattern of production, pattern of consumption, the impact on the environment, the level of openness of the system (dependence on import). All these aspects should be related to an analysis of the effects of these changes on the economic pattern of Mexico. This paper has shown that it is possible to integrate the various pieces of the puzzle in order to elucidate the nature of these dilemmas, increasing in this way the quality of the scientific information used in policy discussion.

Chapter IV Going beyond "efficiency ratios"[5]

IV.1 Abstract

This chapter presents a conceptual analysis that brings together the Relational Analysis and MuSIASEM. MuSIASEM is used to characterize the metabolic pattern across levels of the different constituent components (Giampietro, Mayumi, & Sorman, 2012). It discerns the change of quality of the different stocks/funds and flows. Relational Analysis studies the relation between the different elements of socio-economic systems and nature (González-López & Giampietro, 2017, 2018). In conjunction, both represent a holistic framework (Arodudu, Helming, Wiggering, & Voinov, 2017). The Energy Return on Energy Investment (EROEI) is used as a case study to flag the importance of (i) adopting a diversity of categories of accounting across levels; (ii) characterizing the relations between the different metabolic patterns of the different components; and (iii) integrating non-equivalent views of the same system: the structural (bottom-up) and a functional (top-down). As a result, I present a framework helpful for policy discussion and tacking complexity. It is illustrated in relation to a few energy systems of Mexico. I conclude that EROEI lacks the "functional" perspective, useful for policy discussion. This is necessary to handle the complexity and anticipation of energy systems.

IV.2 Introduction

Because of the complexity of the interactions between socioeconomic and natural processes, it is essential to develop effective tools of energy analysis for defining policy targets and monitoring the results (Giampietro, 2006). More specifically there is a gap in the integration of quantitative analysis studying the efficiency of production of energy carriers and their usefulness in consumption. That is, when considering the overall process of production and consumption of energy carriers

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[5] This chapter builds on the accepted paper for presentation at the 4th International Conference on Energy and Environment: bringing together Engineering and Economics. Guimaraes, Portugal, May 16-17, 2019.

to reproduce social-ecological systems, we do not have a good indicator capable of characterizing the entire process. This indicator would require addressing several relevant aspects: (i) the different quality of energy forms; (ii) the issue of power capacity needed in the set of transformation; and (iii) the difference between flows-stocks and flows-funds (Mayumi & Tanikawa, 2012); (iv) the integration of the different metabolic patterns of the constituent components of society. The adoption of simple ratios calculated at a single scale for measuring "efficiency" misses this complexity of the story (Velasco-Fernández, Giampietro, & Bukkens, 2018).

As explained by Carnot in his seminal book *Reflections on the motive power of fire, and on machines fitted to develop that power* (in which he 'invented' a scientific definition of thermodynamic efficiency) given the epistemological complexity of energetic Systems any quantitative definition of efficiency is ambiguous:

"*We should not expect ever to utilize in practice all the motive power of combustibles. The attempts made to attain this result would be far more harmful than useful if they caused other important considerations to be neglected. The economy of the combustible [***efficiency***] is only one of the conditions to be fulfilled in heat-engines. In many cases it is only secondary. It should often give precedence to safety, to strength, to the durability of the engine, to the small space which it must occupy, to small cost of installation, etc. To know how to appreciate in each case, at their true value, the considerations of convenience and economy which may present themselves; to know how to discern the more important of those which are only secondary; to balance them properly against each other; in order to attain the best results by the simplest means; such should be the leading characteristics of the man called to direct, to co-ordinate the labor of his fellow men, to make them co-operate towards a useful end, whatsoever it may be*" [Carnot (1824)].

The same warning was given by Jevons in relation to the useless of using quantitative assessments of efficiency improvements for making scenarios:

"Now, if the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, *new capital will be attracted,* the price of pig-iron will fall, but the demand for it increase; and eventually the greater number of furnaces will more than make up for the diminished consumption of each. And if such is not always the result within a single branch, it must be remembered that *the progress of any branch of manufacture excite a new activity in most other branches*" (Jevons, 1865).

In the same line Georgescu-Roegen warned about the danger of relying on formal definitions of efficiency, technical coefficients and fixed parameters in predictions about the future. In relation to this point he stated that every time econometric models failed to predict energy demand, econometricians found a ready, yet self-defeating, excuse: "history has changed the parameters . . . but if story is so cunning, why persist in predicting it? (Georgescu-Roegen, 1971).

In conclusion relying on a formal definition of an output/input entails missing the context, that is where the normative side (why/what) comes from.

In conclusion, trying to optimize a whole complex adaptive system by using just a dimension of analysis observing one part of the system only at a given scale means missing the relations that the observed part as with the whole and that the whole has with other systems. Reducing the representation of "efficiency" to a single ratio over two quantities eliminates the possibility of studying the interaction among different Systems. Missing the implications of the relations among Systems removes the information necessary to tackle complexity.

In order to deal with the epistemological complexity of Energy Systems it is necessary to handle the different qualities of energy, its transformation across the pattern of production and consumption of energy carriers, while distinguishing between the functions and structures associated with the identity of the system. To make things more challenging these relations have to be studied across different levels and scales. However, an integrated analysis of the pattern of production and consumption permits to analyze what is the function of the different products, or systems and to properly assess their usefulness.

IV.3 Methodology

IV.3.1 EROEI

EROI or EROEI [Energy Return on the Investment], is the ratio between the quantity of energy delivered to society to the quantity of energy used directly and indirectly in the delivery process

This analysis has been developed mainly by Charles Hall, and used in a variety of applications ranging from oil extraction to the wealth of nations (C. A. Hall & Cleveland, 1981; C. A. S. Hall, 1972; C. A. S. Hall et al., 2011; C. Hall et al., 2009; Rye & Jackson, 2018).

One of the problematic claim is that the same protocol of accounting can be applied across heterogeneous energy systems allowing a global ranking of performance (based on a given interpretation of efficiency) across energy systems.

$$EROEI = \frac{Energy\ delivered}{Energy\ required\ to\ deliver\ that\ energy}$$

In his history this simple ratio has been elaborated in several directions. Lately it has been incorporated in LCA analysis using a bottom-up approach starting from process level data (Murphy et al., 2011) (Murphy, Carbajales-Dale and Moeller, 2016) (Brandt, Dale and Barnhart, 2013) (Brandt and Dale, 2011). EROEI permits also to analyze changes in the characteristics of the process of production through time (depletion).

IV.3.2 MuSIASEM

It is a framework based on complexity theory and the Georgescu-Roegen fund-flow analysis. It explores the metabolic pattern of societal-ecological systems. It argues that societal metabolism is associated with the expression of different metabolic patterns integrated across different levels to reproduce, maintain and keep adaptive the society. This is obtained by establishing a set of impredicative relations between funds and flows stabilizing each other. It characterizes the qualities of the different flows across the different metabolic patterns of the different compartments of society at different levels and keeps congruence among them. This framework makes it possible to define in quantitative terms conditions of internal viability (inside view), external feasibility (outside view) and gives information useful for analyzing desirability.

IV.3.3 Relational Analysis

It analyses the relation between the different constituent components of systems and the whole system while considering the relation between the whole system and its context. These relations determine an emergent metabolic pattern that is associated with the identity of the analyzed system. That is, relational system analysis describes systems as patterns of expected relations over their structural and functional elements developed to fulfill a specific purpose.

The integration of Relational Analysis with MuSIASEM permits the analysis of non-equivalent domains at different hierarchical levels providing a holistic analysis of systems. It analyses the relation between the different metabolic patterns of social-ecological systems between themselves, other social-ecological systems and the environment.

Functional elements

They are associated with the functions determining the interactions between the environment and society.

Figure IV-1 explains the relations among the different elements, stocks, flows, determining the various dynamic matching of demand and supply among the different sectors of society. The quality of the flows varies when used to express the different functions of society. The generation of an emergent pattern of the whole, capable of reproducing itself and preserve its metabolic identity, provides the functional meaning of the given organization of lower level structures. In this metabolic pattern the different flows must be transformed in order to result useful in correspondence with the demanded inputs of functional elements. In resume, in Figure IV-1the connections and the qualitative characteristics of the various nodes explain at the same time, "why" and "how" the system works the way it does.

Structural elements

Structural elements describe the performance and the location of the instances of structural type realized in the system. The metabolic characteristics of these nodes are described both in extensive and intensive terms. The structural part of the systems describes what the system is made of. In resume, how the system does the different thing it does.

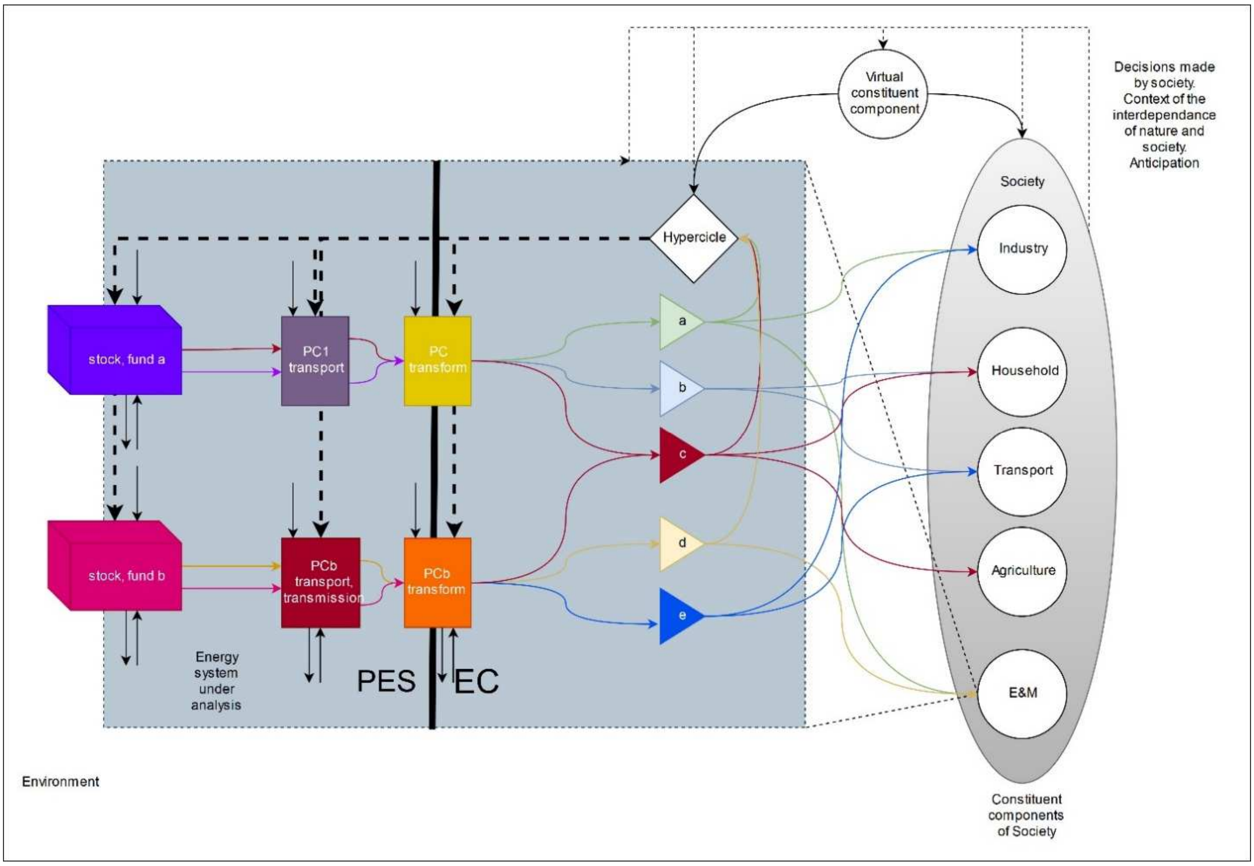


Figure IV-1 Representation of the relations between the different stocks, funds, power capacity, flows and constituent components of society, and the transformation of the quality across the metabolic pathway.

In Figure IV-1The different qualities of the stocks (a,b), Power Capacities of transport and transformation (PC a,b), as well as the different flows transformed (a,b,c,d,e) necessary to reproduce society is represented.

Data sources and organization

Most of the data presented here were obtained from PEMEX (Mexican Oil State Company) through use of the National Transparency System of Mexico (SNT), as the required data is not readily available in common databases. Other sources were the Institutional Database from PEMEX and the Energy Information System from SENER (Mexican Energy Secretariat).

IV.4 Results

In the EROEI ratio, the end use of the different qualities of energy is not represented. I represent this by using the "End-Use Matrix" (Table 1). EROEI doesn’t reflect the quality of the different flows involved in the extraction. The ratios miss the size of the dimension of the different flows (Table 2). For example, the NE region has an EROEI of 20/1 but has the biggest stock of heavy oil (Table 3,4). In the case of the Southern region, it has the smallest EROEI (8/1) but has the more added value type of oil, the superlight oil. In the Northern region, EROEI decreases substantially after transport. The EROEI, in this case, doesn't reflect an important attribute of the region: its very large size. The northern region is the largest. This implies that the delivery of the energy products of this area entails the loss of a significant amounts of energy. It should also be noted that this area doesn't have the largest stocks of oil but it has the largest stock of gas. The cost (both biophysical and economic) of transporting gas and oil are different. The Southwest region has the largest EROEI but doesn't have the largest stocks of anything. However, it has the right mix of the three types of flows found in Mexico. When considering the existing differences between the various regions of Mexico, having different values of EROEI, and after having calculated the average value of EROEI for the whole oil & gas sector in Mexico (it is 6/1 after refining). The question is what is the useful information that is associated with this assessment?

But there is a much serious problem to be considered, in relation to the policy relevance of this indicator. The calculation of a single EROEI problematic when considering the fact that different end uses require different energy flows (different categories of energy carriers). In fact, the usefulness of the primary energy sources (oil and gas) for society cannot be considered when analyzing the overall EROEI of Mexico – i.e. a quantitative assessment of the conversion of Primary Energy Sources (generally summed independently from their quality – heavy oil, light oil or gas - into Energy Carriers independently from their identity – bunker oil, diesel, gasoline, jet fuel, etc.). The usefulness of Primary Energy Sources can only be addressed when looking also at the "End-Use Matrix": what Mexico does with the energy carriers it consumes! This implies that the EROEI can be a useful indicator for commercial companies studying the factors determining both the biophysical and economic costs of the supply of energy carriers (in relation to the characteristics of different primary energy sources). However, it does not provide the required information to study the performance of the energy sector in relation to what is needed by the society.

Coming back to the case study of Mexico, there is another elephant in the room that should be acknowledged in order to flag the useless of the EROEI indicator for national policies. In Mexico half of the heavy oil is exported, and half of the gasoline is imported. This implies that the assessment of EROEI doesn't consider the openness of the energy system and therefore it does not allow to consider important policy implications. For example, when considering energy security, what if an energy sector has a very high EROEI but it is producing a set of energy flows that do not guarantee the energy security of the country? Different energy products can only be obtained from the processing of the different primary energy flows. This information is essential to make informed energy policy. The assessment that the average EROEI of the oil & gas in Mexico is 6/1 doesn't consider that half of the oil is exported, and half of gasolines, petcoke, natural gas, diesel, and gas LP that is imported (Table 1). Put in another way, an assessment based on EROEI generates hypocognition [Lakoff (2010) – i.e. missing relevant aspects of the issue because of the framing of the analysis] that entails ignoring very relevant policy aspects: who is gaining from the favorable EROEI of the Mexican oil? What are the consequences for the Mexican people of the level of openness?

This issue flags elephant in the room ignored when using EROEI as an indicator to inform policy. The analysis of a ratio over “outputs” and “inputs” is based only on quantities of flows. The requirement of power capacity (a fund element) is totally avoided when analyzing the EROEI. In relation to the export of heavy oil and the import of fuels in Mexico the analysis of the fund elements can bring light on the ownership of the technical infrastructures, both for the extraction of the oil and for refining for the production of gasoline. When considering also the fund elements (power capacity), we can see that energy security is not only related to the availability of oil reserves, but also to the availability of refining capacity that can supply fuels at reasonable economic costs.

Last but not least, there is a last elephant in the room ignored by the EROEI indicator. The extraction and processing of Primary Energy Sources into Energy Carriers entails that unavoidable generation of a variety different undesirable byproducts (pollutants) and stress on the environment. These negative side effects - undesirable flows in the oil & gas extraction - are not considered when using EROEI (Table 3-8).

In figure 3 illustrates the different qualities of stocks, funds and flows in the oil and gas system. The identities of the funds, in this case, reflects the qualitative characteristics of the different technologies providing power capacities needed to transform the different stocks and flows across the system. The analysis of the metabolic pattern of a society allows to identify and characterize five essential aspects of the metabolic pattern:

1. the different flows required by the constituent components of the society in terms of quantity, quality, location and timing;

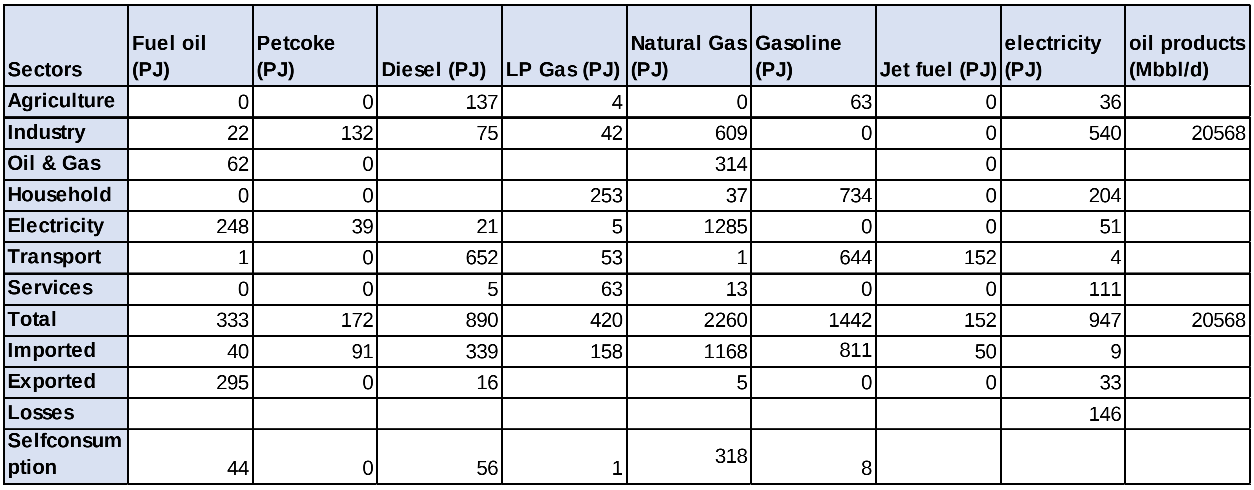
2. the different typologies of power capacities required to transform and transport the different energy flows (table 5-8);

3. the different flows and by-products relevant for the analysis of environmental impact;

4. the fraction of the produced energy carriers that must be re-used inside the energy sector (energy for energy). This quantity is related to the Strength of the Energetic Hypercycle (the return on the investment), that is the basic rationale to which the EROEI refers to;

5. the level of openness of flows that are externalized or internalized from other countries. In the case of imported energy flows – e.g. the fuels imported by Mexico – we can imagine the existence of "virtual constituent components" – e.g. the refineries operating outside Mexico producing the imported fuels. In this case, these "virtual components" are associated with the externalization of the required power capacities and also the externalization of the environmental impact generated by their operations.

Table IV-1 End-Use Matrix. Final consumption of energetics and oil products by societal sub-sectors.



Sectors	Fuel oil (PJ)	Petcoke (PJ)	Diesel (PJ)	LP Gas (PJ)	Natural Gas (PJ)	Gasoline (PJ)	Jet fuel (PJ)	electricity (PJ)	oil products (Mbbl/d)
Agriculture	0	0	137	4	0	63	0	36	
Industry	22	132	75	42	609	0	0	540	20568
Oil & Gas	62	0			314		0		
Household	0	0		253	37	734	0	204	
Electricity	248	39	21	5	1285	0	0	51	
Transport	1	0	652	53	1	644	152	4	
Services	0	0	5	63	13	0	0	111	
Total	333	172	890	420	2260	1442	152	947	20568
Imported	40	91	339	158	1168	811	50	9	
Exported	295	0	16		5	0	0	33	
Losses								146	
Selfconsumption	44	0	56	1	318	8			

In the end use matrix (*Table IV-1*) we can explore the demand for each product and how the demand for each product is different across the different sectors. It establishes a link between the different functions of society and the different functional-structural relations to be established in the energy sectors when transforming PES into EC.

Table IV-2 EROEI and EROEI adding transport for the different extraction regions in Mexico.

Extraction regions	**EROEI**	**EROI+ transport**
OFF SHORE	32	26
NE	24	20
SW	60	52
ON SHORE	13	11
N	59	24
S	8	8
Subtotal	21	18
	EROEI after refining and transport	6

Table IV-3 Metabolism of the oil & gas extraction. Differentiation between the quality of the different internal flows, and outflows, funds, and stocks.

	internal flow	**internal flow**	**internal fund**	**Internal outflow**	**internal outflow**	**Internal outflow**	**internal outflow**	**stocks**
Regions that integrate different functions	Fuel (PJ)	Electricity (PJ)	Works (Mhr)	heavy oil (Mbd)	light oil (Mbd)	Superlight Oil (Mbd)	Gas ft3	Reserves MMboe*
OFF SHORE	60	99	188	1267	510	130	2738	17531
NE	28	99	133	1039	67	0	1412	11531
SW	32	0	55	228	443	130	1326	6000
ON SHORE	50	146	2008	93	260	145	3628	19872
N	18	0	880	65	48	0	2059	4961
S	33	146	1128	28	212	145	1569	14911
Subtotal	110	245	2196	1360	770	275	6366	37403

Table IV-4 Extensive, intensive, Quality of Energy and Power Capacity of the Extraction system.

Level 0 Extraction system				
Level -1 Extraction zones	**Offshore**		**Onshore**	
Level-2 Regions	**NE**	**SW**	**N**	**S**
Extensive variables				
Energy Consumed (PJ)	126.58	32	17.82	178.66
Labor (Mhr)	1.2	0.48	7.7	9.9
CO_2 (t)	15759160	2695046	4197104	2321415
Energy Extracted (PJ)	3059	1924	1046	1482
Intensive variables				
Labor/Energy Extracted (Mhr/PJ)	0.0004	0.0002	0.007	0.007
CO_2/Energy Extracted (t/PJ)	5151	1401	4012	1566
Energy consumed/Energy extracted (PJ/PJ)	0.04	0.02	0.02	0.12
Quality of the Energy consumed				
% Fuel	22%	100%	100%	18%
% Electricity	88%	0%	0%	82%
Source of electricity	Self-generated			grid

Table IV-5 Extensive, intensive, Quality of Energy and Power Capacity of the Refinery system.

Level 0 Refinery system		
Level -1 Refinery	**>heavy**	**>light**
Extensive variables		
Energy Consumed (PJ)	151	145
Labor (Mhr)	91	88
CO_2 (t)	10358800	6110921
Energy Processed (PJ)	1675	1987
Intensive variables		
Labor/Energy processed (Mhr/PJ)	0.054	0.044
CO_2/Energy processed (t/PJ)	6185	3075
Energy consumed/Energy processed (PJ/PJ)	0.09	0.07
Quality of the Energy consumed		
% Fuel	95%	96%
% Electricity	5%	4%
Source of electricity	Almost from	Self-generated
Power capacity		
Power capacity (MMbd)	750	890
% Utilization factor	59%	70%

Table IV-6 Products of the different types of different refineries.

	Refinery function	**LPG gas Mbbl/d**	**Pemex Magna UBA (gasoline) Mbbl/d**	**Pemex Magna (gasoline) Mbbl/d**	**Other gasolines Mbbl/d**	**Pemex Premium (gasoline) Mbbl/d**	**Kerosene Mbbl/d**	**Diesel Mbbl/d**	**Pemex Diesel Mbbl/d**	**Pemex Diesel UBA Mbbl/d**	**light cycle oil Mbbl/d**	**light cycle oil Mbbl/d**	
Cadereyta	heavy-light	1113	53052	6783	0	3248	3335	0	18304	40948	0	0	
Madero	heavy-light	238	0	49341	217	1156	1317	0	36026	0	2452	2288	
Minatitlán	heavy	3470	0	45542	3007	3782	0	164	21029	30017	0	5621	
Salamanca	light	3376	9146	33976	0	1030	9658	0	32088	1529	0	0	
Salina Cruz	light	3809	0	71963	397	7241	14676	0	48369	0	0	0	
Tula	light	9383	26215	53786	0	384	18851	0	35680	10511	0	0	
	Refinery function	**Heavy Fueloil**	**Asfalt**	**Aeroflex 1-2**	**Furfural**	**Lubs**	**Paraffin**	**Petcoke**	**Propylene**	**M. P. Black smoke**	**Sulfur**	**carbon dioxide**	**Anhydrous isopropanol**
Cadereyta	heavy-light	11946	2514	0	0	0	0	15716	1965	1845	813	0	0
Madero	heavy-light	12728	408	0	0	0	0	17622	4531	2425	686	0	0
Minatitlán	heavy	20719	0	0	0	0	0	17392	1975	0	644	0	0
Salamanca	light	36429	8774	217	63	2289	545	2019	314	522	138	360	47
Salina Cruz	light	83485	1539	0	0	0	0	2621	3628	0	357	0	0
Tula	light	72082	4427	0	0	0	0	2892	2268	0	339	0	0

Table IV-7 Products of the different types of gas processing plants.

Gas processing function	**Gas processing plants**	**Etano Mbbl/d**	**GLP Mbbl/d**	**Gasoline Mbbl/d**	**gas mmpc**
>900	**Cactus**	18	21	12	784
>900	**Ciudad Pemex**				681
>900	**Nuevo Pemex**	11	25	14	886
<900	**Morelos**	32	39	11	
<900	**La Cangrejera**	34	43	12	
<900	**Poza Rica**				161
<900	**Pajaritos**	11			
<900	**Matapionche**		1	0	16
>900	**Burgos**		15	18	694

Table IV-9 Extensive, intensive, Quality of Energy and Power Capacity of the Gas processing system.

Level 0 Gas processing system		
Level-1 Gas plants	**>25x10^6 m^3**	**<25x10^6 m^3**
Extensive variables		
Energy Consumed (PJ)	77	10
Labor (Mhr)	53	17
CO_2 (t)	87872	1381
Energy processed (PJ)	1883	394
Intensive variables		
Labor/Energy processed (Mhr/PJ)	0.028	0.043
CO_2/Energy processed (t/PJ)	47	4
Energy consumed/Energy processed (PJ/PJ)	0.04	0.03
Quality of the Energy consumed		
% Fuel	100%	100%
Power capacity		
Power capacity	138x10^6 m^3	34x10^6 m^3
% Utilization factor	69%	59%

Table IV-8 EROEI of the Refining system and the Gas processing system.

EROEI	**System**
8	**Refinning**
22	**Gas processing**
11	**Gas processing and refinning**

IV.5 Discussion

The analysis presented allows to make a few conclusions about the weakness of EROEI when used as an indicator for policy:

1. it aggregates different energy outputs and inputs belonging to different energy forms of different qualities. The choice of a method of aggregation entails an important bias in the results and therefore, it should depend on the purpose of the analysis. When dealing with complex energy system the use of a rigid protocol of accounting generating just a single quantitative indicator makes the resulting assessment practically useless;

2. it does not have a standard criteria for defining the boundaries (there are different values of EROEI depending on the level of analysis considered – e.g. for oil, at the well, with transport, with refinery, depending on the products supplied by the refinery);

3. it does not allow to track the factors determining a change in its value (e.g. changes in the quality of the resources vs changes in the performance of technology;

4. it does not address the issue of scale, the same EROEI can be referred to a huge oil reserve or a small oil reserve;

5. it does not address the type of resource – stock-flow vs fund-flows. That is the same EROEI can refer to oil obtained by depleting a stock or to electricity obtained by exploiting the power of wind;

6. it refers only to the production of energy carriers, this point does not allow a contextualization of the implications of the characteristics of this production in relation to the end uses of the energy carriers;

7. it totally ignores the existence of a lot of other biophysical flows relevant for the analysis of the environmental impact as.sociated with the exploitation of primary energy sources;

8. it does not allow to bridge biophysical analysis with economic analysis. In fact, the loss of information due to the chosen aggregation of different forms of energy inputs and outputs makes it impossible to associate an economic analysis to the information given by the EROEI.

In conclusion the calculation of the EROEI translates into a major loss of information about the different functions that energy transformations guarantee in a society. The network of energy transformation expressed in a metabolic pattern shows the relations between different energy forms used to express different functions in different places at different times at different power levels. The characteristics of this networks are invisible to the EROEI indicator.

In relation to this point, the adoption of the MuSIASEM allows to see the relevant factors of the metabolic pattern, where the relation of the different types of energy qualities, power capacity, human activity, different properties of energetics are considered. Most importantly, in relation to policy relevance, MuSIASEM addresses the key role of the functional essence of energetics – why energy is transformed in the first place.

IV.6 Conclusion

MuSIASEM 2.0, or the intersection between Relational Analysis and MuSIASEM avoids using single ratio assessments (e.g. input/output, output-input), By (A) integrating processes taking place simultaneously at different levels, (B) Adopting different narratives, and by this changing the old imperative of comparing or evaluating different metabolisms, and by this embracing complexity. And (C) studying the relations of the part with the whole, the whole with its environment and other societal systems. This allows a better interaction between the science and policy interface in times where there are multiple agendas to consider.

Discussion

What presented in this thesis is a new form of analysis that permits to characterize the different social-ecological systems and the relations they have among themselves and with nature. What I have tried to do is to avoid the reductionism found in most of the ecological indicators that employ simple ratios, or just give measures without units. I hope that the reader is convinced of the advantages of this strategy after reading my thesis.

Also, what I have developed further is the ability of handling the distinction between the function and the structure of systems. What does this mean when realizing plans for energetic development? In the case of the chapter *Going beyond "efficiency ratios"* I have demonstrated how one of the most employed indicators – the EROEI - misses the functional part. First by not recognizing the distinction between the different energy carriers and primary energy sources, then by not integrating the performance of the different process in the production chain and the demand. This insight is valuable for generating more useful information in energetic planning.

In the *Charcoal metabolism* chapter, I explored how to integrate information from different systems through the implementation of the concept of "processor establishing the nexus among different resources. For example, in the case of the charcoal production in the Laotian village considered in the study, land and human activity can become a constraint when analyzing the energy performance. At the same time, charcoal can change its meaning for the village. From being energy into becoming an asset.

In the *Oil and gas metabolism* chapter, I follow the same line of investigation. The importance of handling the distinction between energy carriers and primary energy sources, while integrating the functional and the structural view of energetic systems. This complex characterization is necessary when a country wants to anticipate the outcomes of the oil and gas production and consumption.

That chapter shows that energetic analysis can permit to elucidate many dilemmas. For example, the it allows to study how Mexican government's goal to increase oil and gas production clashes with the goal of reducing levels of emissions. This type of analysis permits to study the co-existence of different agendas affecting the same system. As in the charcoal production chapter, the nexus between the energy, water and, land was analyzed.

In the last chapter, about *electricity metabolism,* I explored the relation between the function of the different electricity sources, the land demanded and the emissions. And how there are in some sort dilemmas. How renewables sources have low power density and by this, they demand higher quantities of land compared to emission intensive sources. Furthermore, the increase of consumption of natural gas, employed as back-up, may contribute to keep high the level of emissions, and if the pattern of consumption doesn't change it may be end-up by generating a rebound effect. Again, analyzing the relation between different systems can help to better understand and deal with the co-existence of different agendas. There are many tradeoffs when dealing with energy issues. This entails that, focusing on solving one problem contribute to generate it another.

We can see after the development of all these chapters that, as Carnot, Georgescu-Roegen and Jevons warned, we don't have to lose the context. Focusing on just maximizing one dimension can have severe consequences. Also, when analyzing energy systems, it is essential to carefully study their functional side. The identification of the functional role of an energy system is key when planning. As its names recall, the analysis of the function covers the why and what questions. These questions may be more intangible and represent an emergent pattern from the lower level structural components when interacting in the given context. The functional part deals with the final cause and with the explanations of the causal processes inside systems. To anticipate how a system is working, we should incorporate the functional component for planning. Dealing only with the characteristics of the structural components (as done in general by conventional analysis) is reductionist.

Conclusion

I believe that in this thesis I accomplished my main objectives. Non-reductionist tools for energy analysis were developed by incorporating complexity theory through Relational Analysis and MuSIASEM. The approach developed in this thesis helps to tackle dilemmas or trilemmas in energy analysis, and it addresses the spatial perspective when analyzing energy systems while integrating the quantitative information in a holistic framework.

This methodology permits to analyze the implications of the co-existence of different contrasting agendas. A necessary feature for the analysis of the complex problems of sustainability experienced in these days, where each relevant system interacts with many others.

Current energy analysis methodologies generally don't address the functional perspective. This thesis incorporates the analysis of purposes and "final causes" in energy analysis, and this creates useful outcomes for energetic planning.

Examples of results of biophysical analysis carried out across different levels and scales clearly show that reducing energetics into a monetary analysis is dangerous. In this way, we lose a lot of relevant information about the characteristics of the analyzed systems and the interaction among them. The same loss of information takes place when we reduce the energetic analysis of complex systems into the calculation of "efficiency" ratios. In the development of this thesis, I have developed and implemented tools useful for generating anticipatory outcomes. They are useful for gaining better insights in different energetic scenarios especially in the complex reality we're facing at present times.

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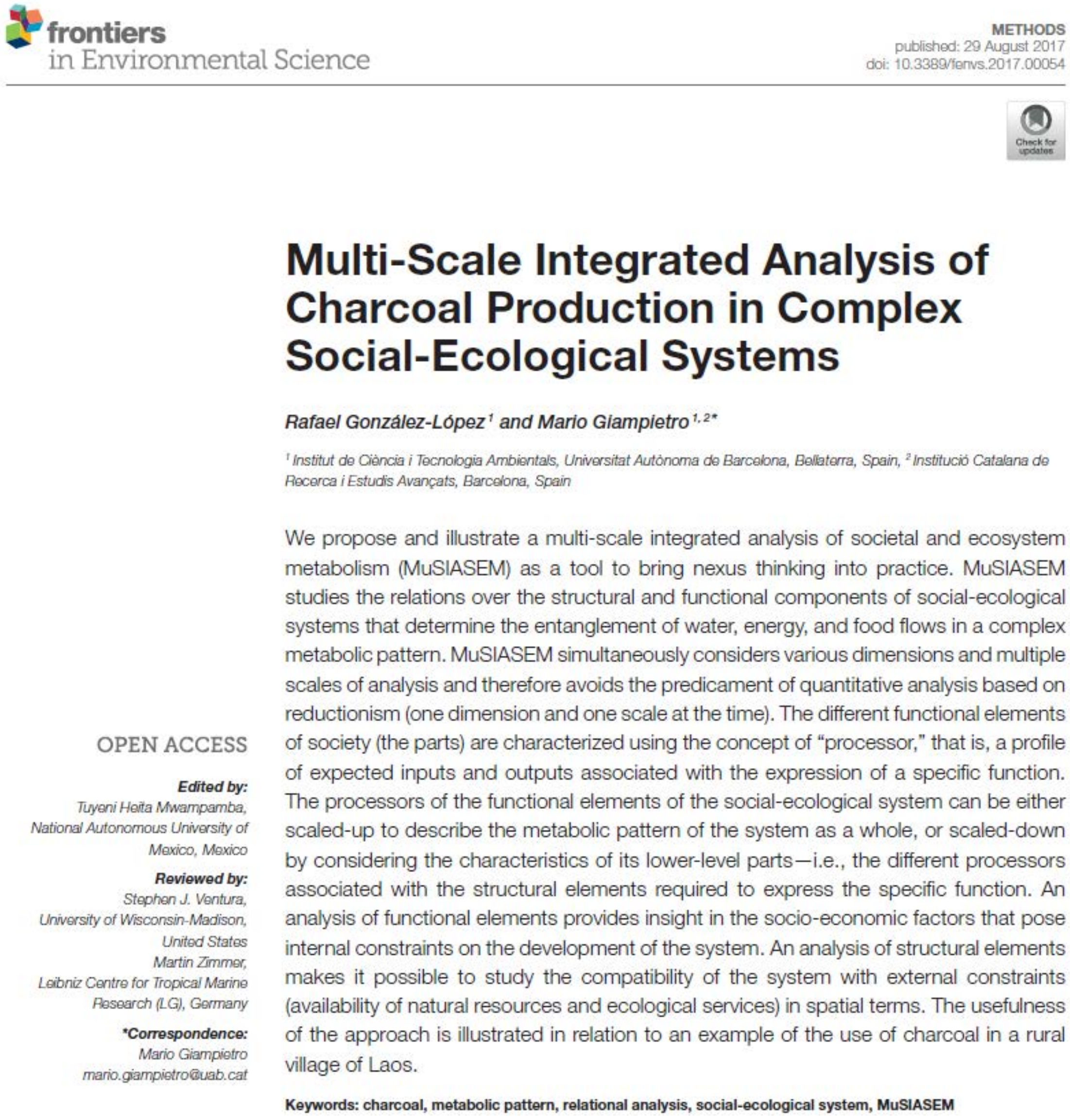
Appendix

Publications



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METHODS
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Multi-Scale Integrated Analysis of Charcoal Production in Complex Social-Ecological Systems

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We propose and illustrate a multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) as a tool to bring nexus thinking into practice. MuSIASEM studies the relations over the structural and functional components of social-ecological systems that determine the entanglement of water, energy, and food flows in a complex metabolic pattern. MuSIASEM simultaneously considers various dimensions and multiple scales of analysis and therefore avoids the predicament of quantitative analysis based on reductionism (one dimension and one scale at the time). The different functional elements of society (the parts) are characterized using the concept of "processor," that is, a profile of expected inputs and outputs associated with the expression of a specific function. The processors of the functional elements of the social-ecological system can be either scaled-up to describe the metabolic pattern of the system as a whole, or scaled-down by considering the characteristics of its lower-level parts—i.e., the different processors associated with the structural elements required to express the specific function. An analysis of functional elements provides insight in the socio-economic factors that pose internal constraints on the development of the system. An analysis of structural elements makes it possible to study the compatibility of the system with external constraints (availability of natural resources and ecological services) in spatial terms. The usefulness of the approach is illustrated in relation to an example of the use of charcoal in a rural village of Laos.

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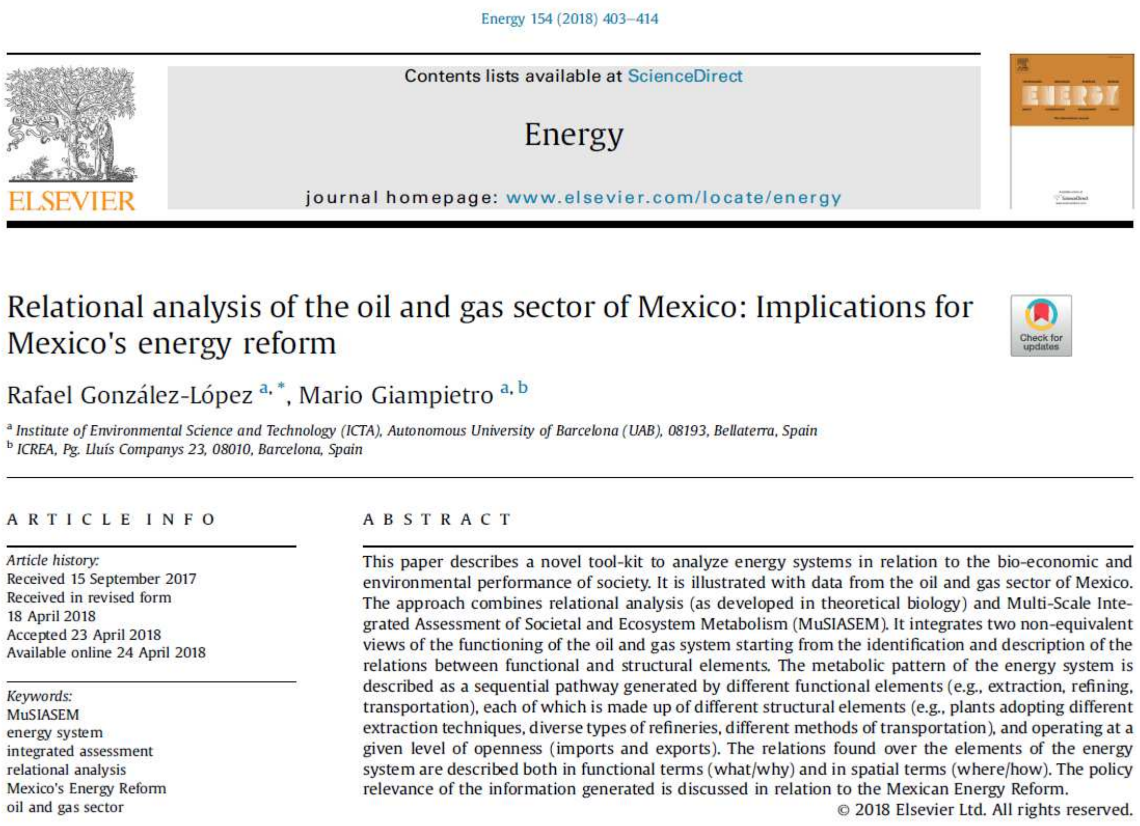
Keywords: charcoal, metabolic pattern, relational analysis, social-ecological system, MuSIASEM



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Relational analysis of the oil and gas sector of Mexico: Implications for Mexico's energy reform

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ABSTRACT

This paper describes a novel tool-kit to analyze energy systems in relation to the bio-economic and environmental performance of society. It is illustrated with data from the oil and gas sector of Mexico. The approach combines relational analysis (as developed in theoretical biology) and Multi-Scale Integrated Assessment of Societal and Ecosystem Metabolism (MuSIASEM). It integrates two non-equivalent views of the functioning of the oil and gas system starting from the identification and description of the relations between functional and structural elements. The metabolic pattern of the energy system is described as a sequential pathway generated by different functional elements (e.g., extraction, refining, transportation), each of which is made up of different structural elements (e.g., plants adopting different extraction techniques, diverse types of refineries, different methods of transportation), and operating at a given level of openness (imports and exports). The relations found over the elements of the energy system are described both in functional terms (what/why) and in spatial terms (where/how). The policy relevance of the information generated is discussed in relation to the Mexican Energy Reform.

Curriculum Vitae

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Curriculum Vitae, May 2019

Citizenship: Mexican
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Education

2015–2019	**PhD candidate**, *Institut de Ciència i Tecnologia Ambientals (ICTA). Universitat Autònoma de Barcelona (UAB).* Advisor: Dr. Mario Giampietro.
2011–2013	**Master in Geography**, *Centro de Investigaciones en Geografía Ambiental (CIGA). Universidad Nacional Autónoma de México (UNAM).* Thesis: Modelado espacial de la dinámica de los bosques de Quercus manejados para carbón vegetal en la cuenca del lago de Cuitzeo, Michoacán *[Spatial modeling of the Quercus forests dynamics, managed for charcoal production in the Cuitzeo Lake basin, Michoacan]*. Advisor: Dr. Adrián Ghilardi. GPA: 9.29 of 10
2006–2010	**BSc in Biology**, *Faculty of Sciences, UNAM.* Thesis: Caracterización biogeográfica de la provincia del Altiplano Mexicano con base en su mastofauna *[Biogeographic characterization of the Mexican Plateau province based on its mastofauna]*. Advisor: Dr. Tania Escalante. GPA: 8.37 of 10

Awards

2013	Graduated with honors. Master in Geography.
2013	Master's thesis proposed for Alfonso Caso medal.

Professional and academic experience

November 2014-August 2016 **GIS and RS technician**, *CONAFOR project*, "Linking local action to international climate change agreements in the dry forests of Mexico".
-Develop Remote sensing methods to monitor forest degradation and deforestation in Ejidos and communities

September 2013-August 2016 **Research Associate**, *Fondo Mixto Conacyt project 192429*, "Monitoreo de la cubierta del suelo y la deforestación en el Estado de Michoacán: un análisis de cambios mediante sensores remotos a escala regional" *[Monitoring land cover and deforestation in the State of Michoacán: an analysis of changes by remote sensing at a regional level]*.
Tasks:
-Image classification. The satellite images from all the state of Michoacan were classified and verified via remote sensing, also the handling of databases.
-Develop new tools to update cartography. It was necessary the use of Postgres, R, DINAMICA EGO and Python during the process.
-Train students. Six students were trained during the project.
-Test new tools (e.g. Berkley segmentation algorithms, R scripts, Qgis plugins).
-A Land Use Land Cover Analysis is in process.
-It is expected to publish all the results on international peer reviewed scientific journals. The next link describes the project:
http://www.ciga.unam.mx/wrappers/proyectoActual/monitoreo/

2013 **Instructor**, *Course: Modeling environmental processes with DINAMICA EGO.*
http://bit.ly/2h9NHhf
- The course was taught to 20 students during one week (35 hours).

Publications

Tania Escalante, Gerardo Rodriguez-Tapia, Miguel Linaje, Patricia Illoldi-Rangel, and Rafael González-López. Identification of areas of endemism from species distribution models: threshold selection and nearctic mammals. *TIP*, 16(1):5–17, 2013.

Rafael González-López and Mario Giampietro. Multi-scale integrated analysis of charcoal production in complex social-ecological systems. *Frontiers in Environmental Science*, 5:54, 2017.

Rafael González-López and Mario Giampietro. Relational Analysis of Energy Systems: An application to the oil and gas sector of Mexico. In Isabel Soares and Joana Resende, editors, *Bringing together economics and engineering proceedings of the 3rd International Conference on Energy and Environment (ICEE 2017): University of Porto, June 29-30, 2017*, pages 672–678. Porto : School of Economics and Management, 2017., Porto, Portugal, 2017.

Rafael González-López and Mario Giampietro. Relational Analysis of the oil and gas sector of Mexico: Implications for Mexico's Energy Reform. *Energy*, 154:403–414, 2018.

Jean-François Mas and Rafael González. Change detection and land use/land cover database updating using image segmentation, gis analysis and visual interpretation. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(3):61, 2015.

Jean-François Mas, Richard Lemoine-Rodríguez, Rafael González, Jairo López-Sánchez, Andrés Piña-Garduño, and Evelyn Herrera-Flores. Evaluación de las tasas de deforestación en michoacán a escala detallada mediante un método híbrido de clasificación de imágenes spot. *Madera y bosques*, 23(2):119–131, 2017.

Jean-François Mas, Richard Lemoine-Rodríguez, Rafael González-López, Jairo López-Sánchez, Andrés Piña-Garduño, and Evelyn Herrera-Flores. Land use/land cover change detection combining automatic processing and visual interpretation. *European Journal of Remote Sensing*, 50(1):626–635, 2017.

Aknowledgments

2011 Escalante, T. y Rodríguez, G. Base de datos geoespacial de mamíferos terrestres de América del Norte: una aproximación a sus patrones biogeográficos y conservación. *[Geospatial database of the terrestrial mammals from North America: an approximation to their biogeographic patterns and conservation]. XIX Reunión Nacional SELPER-México.*

2012 Atlas biogeográfico de los mamíferos terrestres de América del Norte. *[Biogeographic atlas of the terrestrial mammals of North America] http://www.atlasbiogeografico.com/*

2016 Mas, Jean-François, et al. "Comment on Gebhardt et al. MAD-MEX: Automatic Wall-to-Wall Land Cover Monitoring for the Mexican REDD-MRV Program Using All Landsat Data. Remote Sens. 2014, 6, 3923–3943." Remote Sensing 8.7 (2016): 533.

Conferences

2008 XVIII Ecology Students Symposium. **Work:** Effect of intraspecific competition on reproductive structures of Astrocaryum mexicanum.

2010 X Latin American Congress of Mastozoology. **Work:** Biogeographic Characterization of the Mexican Plateau province based on its mastofauna.

2010 Attendance to the XII Autumn School of Mathematics and Biology, and National Meeting of Mathematical Biology.

2010 IX Argentinian meeting of Cladistics and biogeography. **Work:** The correct identification of areas of endemism and presence thresholds in models of potential distribution.

2012 Geography Students Coloquium "Territorialidades diversas y una sola Geografía". CIGA,UNAM. Masters thesis advances were presented.

2013 XX SELPER-MÉXICO National meeting. **Work:** "Modelado espacial de la dinámica de bosques de encino bajo producción de carbón vegetal en la cuenca del lago de Cuitzeo, Michoacán" *[Spatial modeling of the Quercus forests dynamics managed for charcoal production in the Cuitzeo Lake basin, Michoacan].*

2014 IUFRO. Salt Lake City, USA. Measuring tropical forest degradation from high-resolution remote sensing imagery and field data for building a REDD+ MRV system in Mexico.

3/5

2014 ForestSAT. Riva del Garda, Italy. Successive updating of cartographic land cover databases using image segmentation, GIS analysis and visual interpretation.

2015 ISPRS Geospatial Week. La Grande Motte, France. Change detection and land use / land cover database updating using image segmentation, GIS analysis and visual interpretation

2016 Attendance to the American Association of Geographers' Annual Meeting (AAG2016). San Francisco, USA.

2016 The 53rd Annual Meeting of the Association for Tropical Biology and Conservation (ATBC2016). Montpellier, France. Integrated assessment of the nexus between charcoal, food, and water using MuSIASEM (Symposium: Applying the nexus approach to understand tradeoffs and synergies between charcoal, food and water production in tropical forests)

2017 3rd International Conference on Energy and Environment: bringing together Economics and Engineering (ICEE 2017). Porto, Portugal. Relational Analysis of Energy Systems: An application to the oil and gas sector of Mexico.

2019 4th International Conference on Energy and Environment: bringing together Engineering and Economics (ICEE 2019). Guimaraes, Portugal. -Unfolding the complexity of the nexus between land, energy, and emissions in the energy transition: the case of Mexico. -Opening the black box of energy analysis: implementing MuSIASEM with relational analysis

Scholarships

2009-2010 CONACYT, Project: Biogeografía de la conservación de los Mamíferos Neárticos de México 80370. Septiembre 2009 - Agosto 2010. No. de becario: 14333.

2011-2013 CONACYT: Master's scholarship.

2012 CONACYT: BECA MIXTA. Research stay in Yale University. May-June 2012.

2015-2019 SENER-CONACYT Sustentabilidad Energética

Research stays

2012 **School of Forestry**, *Yale University*, Researcher: Robert Bailis.

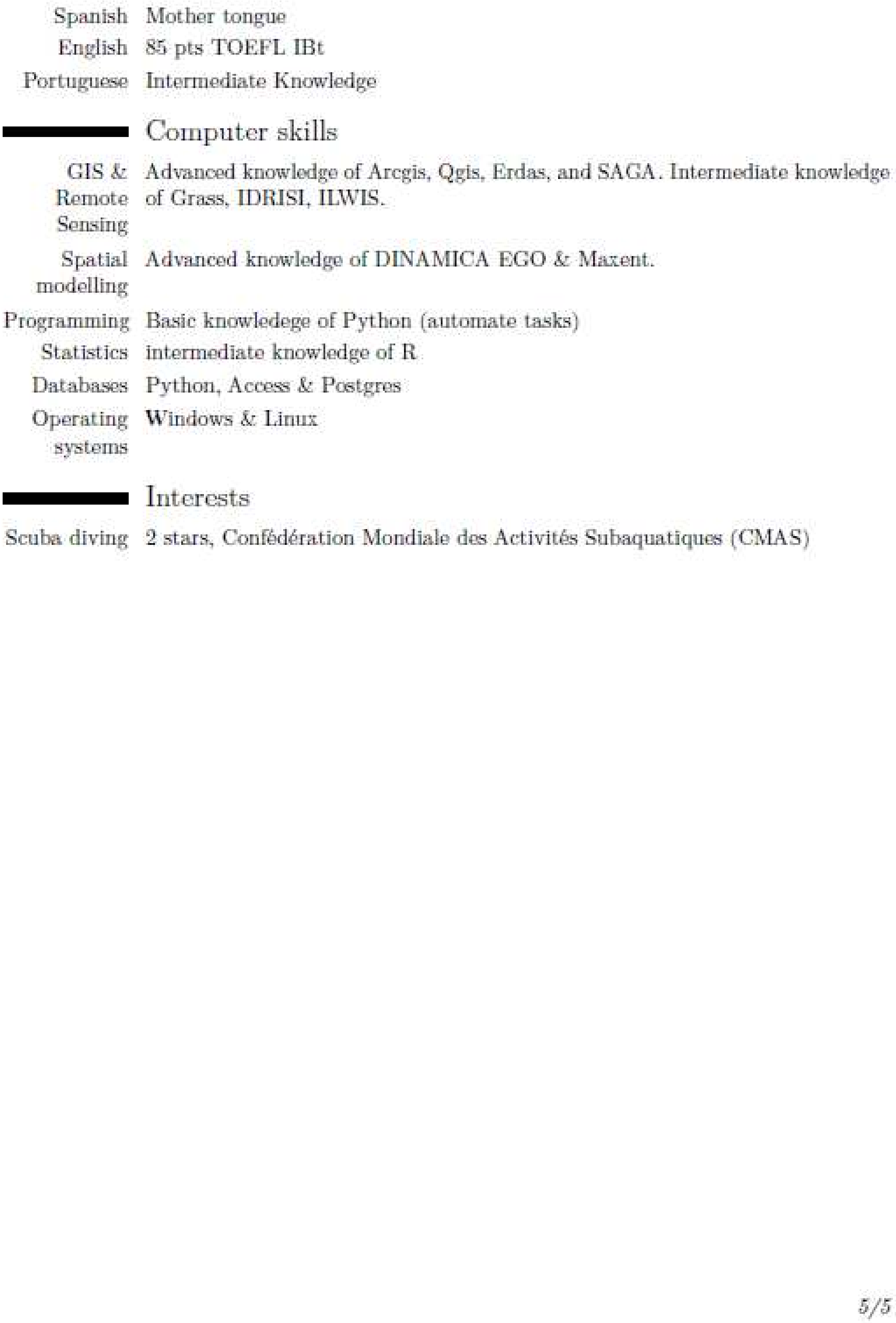
-I stayed two weeks in Yale University planning the fieldwork trip to Honduras. The objective of this fieldwork was to validate a geographic model simulation of the firewood gatherers patterns in Honduras.

-In Honduras I worked with 20 firewood gatherers. The next link is a video that describes the fieldwork. http://www.youtube.com/watch?v=OYS3YxQOqDM

2016 **Centro de Economia Energética e Ambiental (CENERGIA)**, *Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia(COPPE),Universidade Federeal de Rio de Janeiro (UFRJ)*, Researcher: Roberto Schaeffer.

-I stayed 2 months developing a methodology to analyse the energy matrix at the country level. Furthermore, I corroborated the information that I am developing for my PhD thesis with Professor Alexandre Szklo. In specific, information about oil refinery and extraction

Languages



Spanish	Mother tongue
English	85 pts TOEFL IBt
Portuguese	Intermediate Knowledge

Computer skills

GIS & Remote Sensing	Advanced knowledge of Arcgis, Qgis, Erdas, and SAGA. Intermediate knowledge of Grass, IDRISI, ILWIS.
Spatial modelling	Advanced knowledge of DINAMICA EGO & Maxent.
Programming	Basic knowledege of Python (automate tasks)
Statistics	intermediate knowledge of R
Databases	Python, Access & Postgres
Operating systems	Windows & Linux

Interests

Scuba diving	2 stars, Confédération Mondiale des Activités Subaquatiques (CMAS)

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