Energy Policy 126 (2019) 431–443

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

An alternative to market-oriented energy models: Nexus patterns across hierarchical levels

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ARTICLE INFO

Keywords:
MuSIASEM
Societal Metabolism
Water-energy-food nexus
Hierarchy Theory
Science-Policy Interface
Complexity

ABSTRACT

From a biophysical perspective, energy is central to the behaviour of social-ecological systems. Its ubiquity means that energy is entangled with nexus elements, including water, land, emissions and labour. At the science-policy interface, large market-oriented energy models dominate as the tool to inform decision-making. The outputs of these models are used to shape policies, but strongly depend on sets of assumptions that are not available for deliberation and gloss over uncertainties. Taking an approach from complexity, we propose an alternative to market-oriented energy models, describing the behaviour of energy systems in relation to patterns of nexus elements across hierarchical levels. Three characteristics are central to the approach: (i) the distinction of the model's building blocks into functional and structural elements; (ii) their hierarchical organisation and (iii) the description of nexus patterns at each level, through the tool of the *processor*. To illustrate the model, it is applied to Catalonia's energy sector, linking production and consumption patterns. The framework may help inform stakeholder deliberation on pressing energy and nexus issues.

1. Introduction

A biophysical reading of societies describes their behaviour in relation to the extraction, exchange, distribution and consumption of material flows (Cleveland, 1987). From a biophysical perspective, energy lies at the core of how societies function, providing the input for all economic processes and regulating the interface between societies and natural ecosystems (Ostwald, 1907; Lotka, 1922; White, 1943; Cottrell, 1955; Odum, 1971; Georgescu-Roegen, 1971; Smil, 2010). The ubiquity of energy means that it is closely linked to pressing problems faced by social-ecological systems (SESs), including climate change, security, resource depletion, justice and poverty.

Two recent trends in energy studies and assessments have aimed at moving the framing of energy issues from a single-sector, monodisciplinary one, towards integrated and holistic descriptions. The first trend, at the level of energy studies, is a move from the dominant engineering framing of energy to one that includes wider social views (Sovacool, 2014), recognising the links of energy to social issues and to the functioning of society beyond its biophysical dimension. The second trend, at the level of energy assessments, is a move towards integrated assessments that handle multiple types of variables at once, such as water, climate, land, food and economic variables. These kinds of approaches can be grouped under the umbrella term of *nexus assessments*. The surge in popularity of the nexus in academic discourses has been rapid (Bazilian et al., 2011; Ringler et al., 2013; Howells et al., 2013; Endo et al., 2015; Howarth and Monasterolo, 2016; Kurian, 2017), and fits within scientific moves towards holistic approaches and interdisciplinarity (Lam et al., 2014). In relation to nexus assessments, Stirling (2015) highlights the need to view sustainability challenges as complex ones, where “it is ever more clearly understood that circumscribed monodisciplinary or single-sector approaches are not enough”.

At the science-policy interface, and in particular in EU policy, moving away from the monodisciplinary, mostly technical, arena to which energy has been historically confined to has not been simple (Giampietro et al., 2013). When it comes to framing energy beyond its biophysical dimension and considering it as a social issue, some progress has been made with the recent Clean Energy for All Europeans package (European Commission, 2016a), which includes discourses of energy poverty and a focus on citizens’ rights with respect to energy services. When it comes to handling multiple elements linked to energy

Abbreviations: SES, Social-Ecological System; GHG, Greenhouse gases; PES, Primary Energy Source; EC, Energy Carrier; EU, End Use; MuSIASEM, Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism; CUF, Capacity Utilization Factor; OECD, Organisation for Economic Co-operation and Development; WELMM, Water, energy, land, materials and manpower; PWR, Pressurised water reactor; PV, Photovoltaic; CC, Combined cycle; CHP, Combined heat and power; WWTR, Waste water treatment and reuse; PHS, Pumped hydroelectric storage

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https://doi.org/10.1016/j.enpol.2018.11.002
Received 20 February 2018; Received in revised form 24 September 2018; Accepted 2 November 2018

through nexus assessments, a *linearly interactive* (interdisciplinary) approach has been taken to inform EU policy, whereby different models specialising in the accounting of different elements provide the input for other models specialising in other elements, and so on. The EU 2016 Reference Scenario, the EU's most recent modelling exercise informing policy-makers on energy, transport and climate issues, gives an example of the concatenation of inputs and outputs between models: "PRIMES uses as inputs macroeconomic and multi-sectorial projections from GEM-E3 and projections of world energy prices from PROMETHEUS. PRIMES conveys projections to GAINS, GEM-E3 and CAPRI" (European Commission, 2016b, p.16). PRIMES is a market-oriented energy model, GAINS is a GHG emission model, GEM-E3 is a general equilibrium macroeconomic model and CAPRI is an agricultural sector model.[1]

Whilst concatenating inputs and outputs of different models provides a form of interdisciplinarity, the inner workings of the models themselves are not open for deliberation. Taking a view from complexity, which can be defined as the existence of plural, legitimate and irreducible representations of the same issue (Simon, 1962; Whyte et al., 1969; Rosen, 1991, 2000; Ahl and Allen, 1996; Kovacic, 2017), we argue that moves towards interdisciplinarity in energy studies should recognise that the same energy issue can be viewed with different framings depending on the stakeholder's perspective and priorities. As a consequence, models informing decision-making should allow for deliberation at various steps of the analysis, rather than providing a normative set of outputs. According to complex systems theory, different quantitative representations depend on different pre-analytical choices of scale and dimensions of analysis – i.e. the adoption of non-equivalent descriptive domains (Giampietro et al., 2006). This implies that the results of quantitative analyses developed within non-equivalent descriptive domains are not reducible to each other (Rosen, 1991). This conceptual impossibility forces analysts to adopt a series of "heroic assumptions" about expected relations associated with large doses of uncertainty (Funtowicz and Ravetz, 1990; Pereira & Funtowicz, 2015). In the models informing EU policy, assessment of the robustness of their assumptions and implications are impossible as the modelling codes are not available to the public, such as the PRIMES modelling codes used to build EU energy scenarios. Hidden assumptions, which could become contested if made explicit, lead market-oriented energy models to "provide normative optimised scenarios, in which real implementation bottlenecks are ignored (e.g. uncertainty, heterogeneity of decision makers and market imperfections)" (Dodds et al., 2015, p. 85). This is a general problem associated with the concept of so-called *evidence-based policy* (Ravetz, 1971; Rayner, 2012; Saltelli and Giampietro, 2017).

Thus, our model aims to assess nexus elements simultaneously within a coherent framework capable of integrating information coming from different descriptive domains, and from different stakeholders. In this way, we avoid what Cairns and Krzywoszynska (2016) have defined as *integrated imaginaries*, whereby nexus assessments are used to push for technocratic win-win solutions. All the opposite, a transparent framing of assumptions across hierarchical levels may generate uncomfortable knowledge for policymakers, showing that win-win solutions are rarely possible.

The aim of the paper is methodological: building on the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) (Giampietro et al., 2012, 2013, 2014), we propose a method of integration of quantitative information that handles multiple nexus elements across different levels of the energy system. What defines the model is not the choice of categories and variables, but the way in which nexus patterns are linked across hierarchical levels. Two key distinctions are maintained throughout the analysis: between structural and functional elements of the energy system, following the Koestler's notion of holons (Koestler, 1968, 1978), and between funds and flows, following Georgescu-Roegen's flow-fund model (Georgescu-Roegen, 1971). We explain the model through the case study of Catalonia's energy sector. By introducing numbers associated to a case study, we show how the methodology could be suited in addressing different types of policy questions.

The rest of this paper is structured as follows: Section 2 provides a review of current energy assessment frameworks dealing with multiple nexus elements (2.1) and introduces the key principles of energy analysis in MuSIASEM (2.2); Section 3 outlines the rationale of the model, starting with its building blocks (3.1) and explaining how the building blocks are linked across hierarchical levels (3.2), through which equation (3.3) and within which boundaries (3.4). Section 4 introduces the data used in the example (4.1) and provides an overview of the case study (4.2). Results and Discussion are presented in Section 5, starting with the production mix (5.1) and linking it to consumption patterns across different economic sectors (5.2). The discussion section focuses on the model's uncertainty (5.3) and on its policy relevance (5.4).

2. Background and literature review

2.1. Energy-nexus assessments

From a systems perspective, various modelling tools integrating energy assessments with other nexus elements have been proposed, as summarised by Keairns et al. (2016). These include the Climate Land-use Energy and Water Strategy (CLEWS) modelling framework, the Stockholm Resilience Center's Water Energy and Planning (WEAP) system, the Institute for Applied System Analysis' Model for Energy Supply Systems and their General Environmental Impact (MESSAGE), the Integrated Model to Assess the Global Environment (IMAGE), the Water Energy Land Material and Manpower (WELMM) and, finally, the Multi-Scale Integrated Analysis of Society and Ecosystem Metabolism (MuSIASEM). Of these, CLEWS, MESSAGE and IMAGE are integrated assessment models (IAMs) with common characteristics: they produce long term scenarios with a global focus, employ optimisation models, are highly detailed and, although describing the interactions between human and natural ecosystems, they do not consider labour as a variable. IAMs are widely used to develop scenarios for the IPCC as they model climate change in relation to a diverse set of social and physical variables. WEAP, on the other hand, is mostly concerned with integrated assessments of water.

WELMM and MuSIASEM present many similarities among them, and differences to the IAMs mentioned above. Their common characteristics are the disaggregation of types of energy (electricity, heat and fuels), which are considered as separate variables, the introduction of labour as a variable in the system and a simple analytical approach that is accessible to decision-makers. Operating at a scale of *middle numbers* (between the process scale and the system level), MuSIASEM distinguishes itself for the lack of closed semantic descriptions of its categories, which may be decided with stakeholders, and for using a coarse-grained approach that allows understanding the big picture (at a given level of representation) without losing details that are relevant to the policy process (at a different level of representation). In the next section, the main characteristics of energy assessments in MuSIASEM, on which our model builds on, are outlined.

2.2. MuSIASEM

The foundation of energy assessments with MuSIASEM is to acknowledge the complexity of the concept of energy, which is semantic in its nature. MuSIASEM calls for at least three non-equivalent ways of accounting for energy flows consumed by society, all of which are needed to assess the performance of an economy (Giampietro et al., 2013). Primary Energy Sources (PES) are what is required from boundary conditions - they are sources outside of human control, such

[1] For an overview of the main characteristics of each model, see (European Commission, 2018).

as the amount of oil and coal in the earth's lithosphere; energy Carriers (EC) are the flows used for transformations under human control, for example electricity, heat and fuels; Energy end-uses (EUs), finally, are characterisations of a specific pattern of energy carriers for a specific task (what the energy carriers are used for in society). In MuSIASEM this characterisation requires combining assessments of quantities of energy to assessments of quantities of other inputs required for achieving an expected task. In addition to the conceptualisation of different energy flows describing energy transformations in society, MuSIASEM distinguishes between two types of energy forms: thermal energy (e.g., MJ of fuels) and mechanical energy (e.g., kWh of electricity). This distinction applies to both primary energy sources and energy carriers. Finally, MuSIASEM categorises relevant elements of energy systems into funds, flows and stocks, following Georgescu-Roegen's flow-fund model. Funds are elements whose identity remains intact over the chosen scale of analysis, flows are elements that either enter the system without exiting or exit it without entering, and stocks are non-renewable supplies from which flows can be extracted. On a yearly timescale of the energy system, for example, labour and land are funds, water and electricity are flows, and oil reserves are stocks.

Recently, MuSIASEM has evolved to include the tool of the *processor*, i.e. an element in the metabolic network that processes a series of inputs and generates a series of outputs at a given hierarchical level. The concept of processor was first introduced in relational analysis by Robert Rosen as a way to identify the relation between functional and structural elements, arising from the definition of a shared final cause (purpose) (Louie, 2010). In this sense, processors represent a bridge between semantic and quantitative definitions. They have been implemented within the MuSIASEM framework and applied to the description of Brazil's oil and gas sector by Aragão and Giampietro (2016), by González-López and Giampietro (2017) to the case of charcoal production in Mexico, by González-López and Giampietro (2018) to the case of the gas and oil sector in Mexico and by Parra et al. (2018) to the description of Ecuador's oil extraction metabolism. At a larger scale, processors have been used to anticipate changes in the social structure in relation to agriculture by Giampietro (2018). While their framing as a tool for nexus analysis is novel, similar tools have been used under different names in other fields (see, for example, nodes in neural networks, enzymes in biochemistry, and production functions in economy). A notable example of a previous conceptualisation of a processor is the "resource processing system" by Grenon (1978) as a tool for the WELMM method. However, to the authors' best knowledge, Grenon's tool has not been applied in recent times to carry out nexus assessments.

3. Methodology

3.1. Building blocks of the model: structural and functional processors

Building on MuSIASEM's recent advancements, our model's building blocks are processors of the energy system, split into functional and structural ones. A *functional processor* can be defined in notional terms as a node in a network that metabolises inputs from the technosphere and the biosphere, and produces outputs, both useful (to society) and released to the environment (e.g. emissions). At the same time, we can describe a *structural processor*, in technical terms, as the profile of inputs and outputs associated with the operation of a structural element – i.e. a given technology expressing a biophysical set of transformations. Fig. 1 shows an example of two of the processors of this case study, the structural processor of a nuclear pressurised water reactor (PWR) and the functional processor of generation of baseload electricity. There is no 1:1 mapping between the characteristics of processors describing structures and functions: the same function can be covered by a mix of different structures, and the same structure can cover more than one function.

The processor relates internal inputs and outputs to external ones.

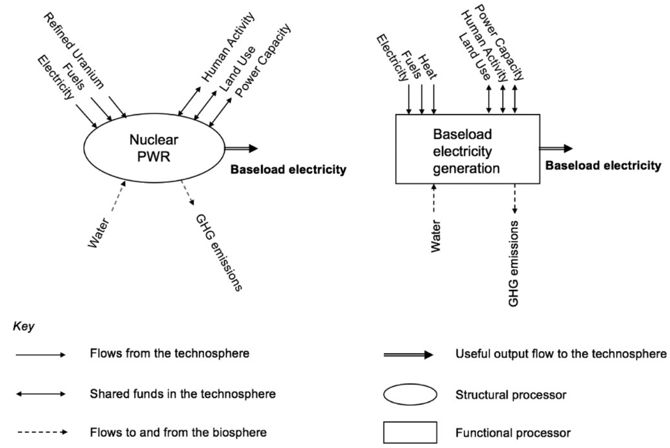

Fig. 1. Examples of a structural and a functional processor - Nuclear PWR and Baseload electricity generation.

Internal inputs are elements that are consumed or produced (flows) and maintained (funds) by society, therefore under human control – they are inside the technosphere. They are represented on the upper half of the processor: flow elements on the left and fund elements on the right. *External flows* are elements that are produced or received (flows) by processes outside human control – they are metabolised outside the technosphere, requiring a supply and sink capacity (funds or stocks) to be provided by the biosphere. They are represented on the lower half of the processor: flows associated with a required supply capacity on the left, and flows associated with a required sink capacity on the right. There is no reference to fund elements on the lower half of the processor, as the fund elements required for guaranteeing the supply capacity and sink capacity belong to the biosphere (they are operating in processes outside human control).

Each processor built for the analysis is associated with five sets of elements:

1. Flows under human control, coming to the processor from the technosphere, for example electricity from the grid consumed in the nuclear plant;
2. Funds under human control, embedded in the technosphere, such as the land on which the power plant is built;
3. Flows extracted from the biosphere, such as the freshwater abstracted for cooling;
4. Flows released into the biosphere, e.g. GHG emissions;
5. Flows generated by the processor for societal consumption, in this example a flow of baseload electricity.

Flows are either produced by funds or extracted from stocks, therefore they relate funds and stocks to processes. Funds, on the other hand, are shared. Shared funds in the biosphere have a level of sink capacity that must be maintained, while funds in the technosphere are shared among the different processes taking place in society. This implies the existence of an internal constraint – i.e. an opportunity cost - for the utilisation of internal inputs in the processors: the amount of labour or land that a process can use depends on how much is being used by others. For example, limits to the amount of land available for biofuel crops can be defined by the amount of land needed for agriculture.[2] External constraints to the behaviour of the metabolic pattern

[2] While the limit of total land available in a country is an external one, outside of human control, limits as to how much land is available for a given process given the land used for another are internal ones, since they are not dictated by the biosphere but by the allocation of shared funds across different sectors – there may be enough land to produce biofuels (no external limits), but it may already be occupied by agricultural production (internal limit).

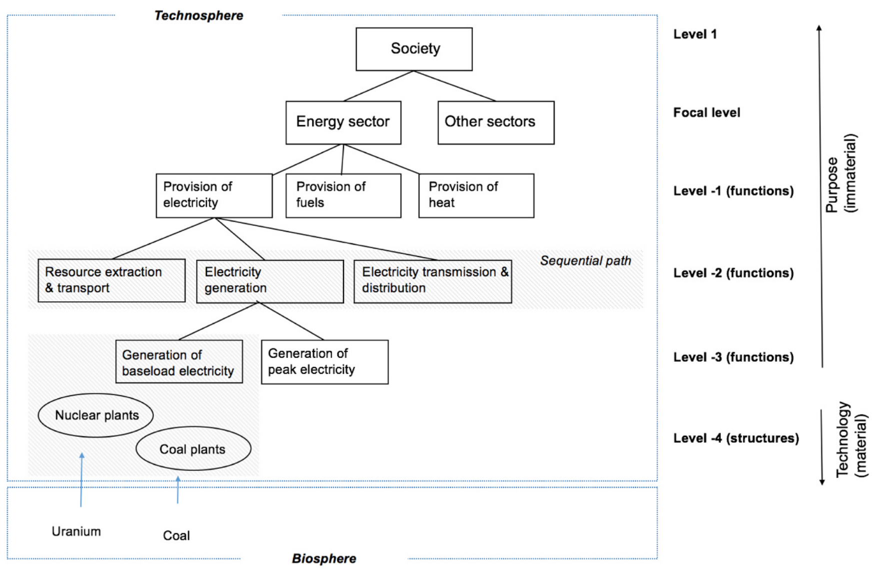

Fig. 2. Example of a hierarchical organisation of the energy system.

of societies are determined by limits in the biosphere, such as the exhaustion of the stock of crude oil on the supply side, or the excessive amount of GHGs released into the atmosphere on the sink side.

3.2. Relations between processors across hierarchical levels

A hierarchy is "a system that is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem" (Simon, 1962, p. 468). Fig. 2 illustrates the energy system broken down across hierarchical levels, populated by structural and functional processors. In this case the hierarchical organisation is nested, as all the lower-level components are aggregated into higher level ones, and organisational, as moving up in hierarchical levels does not necessarily imply moving up in size, and aggregations between elements are purely definitional and context-dependent.

Connecting components of the hierarchy, hierarchical pathways are vertical ones that move up or down levels, linking primary energy sources (uranium and coal, in the figure), to technologies producing and consuming energy carriers and to their purposes. Therefore, they cross the border between the biosphere and the technosphere. Sequential pathways, then, are those operating in sequence at the same level to fulfil a unitary function. For example, in order to provide electricity to society, resources must be extracted, then converted to electricity, and finally transmitted and distributed.

In the figure, only one hierarchical pathway has been expanded, from uranium and coal, to nuclear and coal plants, to the generation of baseload electricity[3] needed in society.

Functional processors are represented in Fig. 2 as rectangular, while structural ones are oval. By structure, we refer to all parts of the system that have been realised in a physical instance. For example, specific technologies or human beings are structures. Functional elements are aggregations of structural ones based on the role they play in the system. Both nuclear plants and coal plants can be used to provide baseload electricity to society, therefore the two structural elements can be grouped into a functional one occupying a higher hierarchical level and labelled "generation of baseload electricity". In this organisation, as mentioned previously, there is no 1:1 mapping between structures and functions: the same structure can be used to cover multiple functions, such as refineries producing heating fuels and transport fuels, and the same function can be produced by a different combination of structures.

[3] See footnote 4.

3.3. Modelling equation

Data taken at the structural level is aggregated and combined to describe the behaviour of the energy system at the functional level, and at the whole, moving from the lower level to the upper level in the hierarchical map. The relations among different hierarchical levels follow simple rules of aggregation. The equation below shows how patterns of nexus elements are scaled across levels of analysis.

$$E_{i,n} = \sum_i E_{i,n-1} \bullet S_{n-1,n} \bullet P_i$$

$E_{i,n}$ represents the set of nexus elements at the level n, so could be, for example, water use or GHG emissions, depending on the index i. The value at a given hierarchical level n is equal to the aggregation of all values of the same nexus elements at the level $n\text{-}1$, multiplied by a scaling factor $S_{n\text{-}1,n}$ and the relative contribution of each element, expressed as a percentage, P_i. This equation holds for intensive variables, for example GHG emissions expressed in terms of emissions per kWh of electricity produced. An intensive description of the sytem's processes is necessary to build scenarios. When the model is used for descriptive purposes, processes may be described in extensive terms. When aggregating extensive variables across hierarchical levels, a simple sum of the lower level elements is required (therefore both S and P are set to one). The scaling factor takes into account economy of scale effects when moving up in size, and is needed when using the model to build scenarios. Given the descriptive purpose of the case study of Catalonia, the scaling factor has been kept to one across levels.

3.4. Boundaries of the case study

The modelling framework does not imply a specific set of boundaries, which can be expanded or compressed depending on the goal of the analysis. The case used as an example here is the energy sector of the Autonomous Community of Catalonia, located on the north-eastern extremity of the Iberian Peninsula, for the year 2012. For the chosen case study, we do not consider every step of the energy system's sequential pathways, but focus on describing the steps that happen within the geographical boundaries of Catalonia, i.e. production of electricity, heat and fuels. There is some minor extraction of crude oil in Catalonia that is not considered in this instance. To further simplify our example, we do not describe transport, transmission and distribution of energy carriers, focusing on the production and consumption of energy carriers within the geographical boundaries of Catalonia.

4. Case study

4.1. Data sources

To frame the description of Catalonia's energy sector, in addition to bottom-up data, top-down data is also collected. We refer to top-down data as data collected through statistical bodies, and to bottom-up data as data collected for instances of power plants, refineries and other structures, mostly through reports. Top-down energy statistics were collected from the Catalan Institute of Energy (ICAEN). Different sources of bottom-up data were used to characterise processors.[4] When possible, data specific to individual power plants, and of the correct year (2012) were used. Neither data collected through reports nor data obtained through statistical offices include uncertainty ranges, and since the focus of the case study is to explain the methodology rather than to present numbers, a sensitivity analysis of the numerical inputs and outputs is beyond our scope. However, Section 5.3 presents a methodological discussion of uncertainty within the model.

4.2. Overview of Catalonia's energy system

Table 1 shows a summary of top-down statistics characterising Catalonia's energy sector in 2012. In the first part of the table, extraction data of PES, as well as net imports, are provided. Following the MuSIASEM distinction between PES and EC, the second part shows refinery process outputs of fuels and heat products, and production of electricity, with their respective net imports. Catalonia produces most of its electricity, while importing almost all of its crude oil and natural gas supply. For heating and transport fuels, there are differences among different elements, with a high production of gasolines and gas-oils and imports of naphtha, fuel-oils and biofuels. This characterisation is similar to other EU countries that are poor in natural resources and have a large amount of power plants as well as complex refining capacity,[5] therefore importing PES to produce EC.

To have on overview of the process of electricity production within the boundaries of Catalonia, Table 2 is introduced. Each type of power plant is associated with its installed capacity, gross electricity generation and capacity utilisation factor (CUF).[6] Nuclear power produces over 50% of Catalonia's electricity, and CUFs of different types of power plants vary between 18% for hydropower and 19% for Solar PV (lowest) to 87% for nuclear and 92% for Pig Manure (highest). In our example, only the power plants accounting for a minimum of 5% of the total installed capacity are considered. The CUFs are an important proxy to determine the function of different types of technologies: a low CUF, paired with a non-renewable resource, usually means that the plant has been used to cover peak demand (such as natural gas combined cycle plants, in this case). Similarly, high CUFs from non-renewable resources imply that the power plant is producing electricity used to cover baseload demand. For variable sources, the CUF alone does not provide a satisfactory indicator of the role played by the electricity production system: the low CUF of solar panels, for example, does not mean they are used to cover peak demand, but is a reflection of the intermittency of the PES.

[4] All sources of bottom-up data are included in the *Appendix*.

[5] We refer to complex refineries as refineries which produce a large variety of petroleum products from crude oil, i.e. those that use thermal or catalytic cracking, or deep conversion processes. For more on refinery complexity, see EIA (2012).

[6] Defined as the ratio of the output of the plant in a year over the maximum electricity it could have produced in the same year.

Table 1
Top-down characterisation of Catalonia's energy system.
Source: ICAEN (2012), Focal level.

Type	Label	Unit	Production	Imports-Exports
Primary Energy Source	Coal	ktoe	23	10
Primary Energy Source	Oil	ktoe	149	10113
Primary Energy Source	Natural Gas	ktoe	1	5961
Primary Energy Source	Non-renewable industrial waste	ktoe	112	0
Primary Energy Source	Uranium[a]	tU	0	63
Energy carrier	Refinery gases	ktoe	0	0
Energy carrier	GLP	ktoe	364	260
Energy carrier	Naphtha[b]	ktoe	-27	2157
Energy carrier	Gasolines	ktoe	1362	-495
Energy carrier	Kerosene	ktoe	871	244
Energy carrier	Gas-oil	ktoe	2991	840
Energy carrier	Fuel-oil	ktoe	1588	-1193
Energy carrier	Biogas	ktoe	64	0
Energy carrier	Biofuels	ktoe	28	303
Energy carrier	Electricity	TWh	45	4

[a] Imports of uranium are not provided in statistical tables and have been derived by assuming that 0.73 kg of Uranium are needed for each TJ produced in a nuclear pressurised water reactor (PWR) (Dones et al., 2007).

[b] Negative values in the production of energy carriers refer to fuels and heat products that are consumed in the intermediate refinery process, where the total consumption is higher than the refinery output (since only net outputs are available through ICAEN, similarly to how only net imports are available, leading to negative imports-exports balances).

Table 2
Characterisation of Catalonia's electricity sector.
Source: ICAEN (2012) Level −1.

	# of plants	**Installed Capacity (MW)**	**Electricity (GWh)**	**CUF[a] (%)**
Natural gas combined cycle (CC)	9	4112	8342	23
Nuclear	3	3147	23,996	87
Hydropower	335	2361	3653	18
Wind	44	1258	2691	24
Combined Heat & Power (CHP)	135	1021	5896	66
Solar PV	N/A	249	406	19
Pig Manure	6	92	738	92
WWTR	16	66	413	72
Urban Solid Waste	4	46	139	34
Concentrated solar thermal	1	24	0,6	0
Landfill	6	19	80	48
Industrial Waste	4	18	N/A	N/A
Eco parks	6	17	56	37
Forest Biomass	2	4	24	69
Waste treatments on farms	9	3	18	65
Total	580	12,440	46,456	

[a] CUF calculated as: (Electricity kWh/Installed Capacity kW) *(100/8760).

5. Results and discussion

The model is built by aggregating lower-level structural elements into a higher level functional description. Mirroring Fig. 2, Fig. 3 shows the hierarchy of functions and structures considered in this case study – we will refer back to it consistently throughout the description of the various steps of the model, as we move from the description of technologies in relation to nexus patterns, to the description of the energy sector as a whole and its relation to other economic sectors.

5.1. Production mix: structural and functional processors

The first step in the analysis is to build structural processors for different energy technologies fulfilling the role of electricity, fuel and

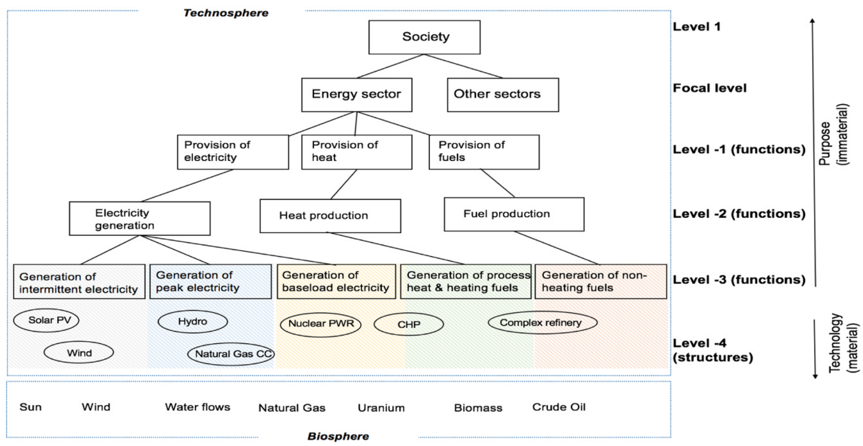

Fig. 3. Hierarchy of structures and functions for the case study of Catalonia.

heat generation. Structural processors can be defined either for specific instances of a technology, e.g. a specific oil extraction platform, or for a type, e.g. for off-shore oil extraction platforms in Europe. The choice of the types to be included in the taxonomy depends on the purpose of the analysis. Since our purpose here is to give an overall description of the energy system, we present a generic structural description of the system, by including the main typologies of power plants, i.e. those that account for at least 5% of the total installed capacity. These are: Combined Heat and Power (CHP) plants, Nuclear Pressurised Water Reactors (PWR), Natural Gas Combined Cycle (CC) plants, Small Hydropower Plants (< 1 MW), Regular Hydropower Plants (> 1 MW), Pumped Hydroelectric Storage (PHS), On-Shore Wind Turbines and Solar Photovoltaics (PV) for electricity production. For fuels, there is an overlap between the type and the instance, as there is only one refining complex in Catalonia, so there is no need to build a typology (data is collected directly for the specific instance).

In MuSIASEM, heat refers to either process heat or heating fuels. Examples of heating fuels include refinery gases and petroleum coke. In Catalonia, there are no processes producing singularly either of these, therefore the functional element "heat generation", which can be further broken down into "process heat generation" and "heating fuels generation", is fulfilled by CHP plants and refineries. Once the structural typologies are chosen, processors are built by defining a pattern of inputs and outputs associated with each technology. The following set of inputs and outputs is considered for each type:

1. Flows from the technosphere: electricity and fuels;
2. Flows from the biosphere: water;
3. Technosphere funds: land use, human activity (intended as labour) and power capacity;
4. Flows to the biosphere: GHG emissions.

Therefore, each processor represents a pattern of the water-energy-land-labour-climate nexus. We consider the water that is consumed during the process, not including water withdrawn and then released. This means, for example, that the water flow input for hydropower plants represents the water evaporated during the process, and not the water passing through the dam. Labour, labelled as Human Activity, includes the working hours spent to produce the output (thus plant manufacturing is not included) and does not include indirect jobs – therefore, it describes the labour of operation & maintenance (O&M), and management overhead, accounted for in hours (h). Climate is addressed by accounting for the GHG emissions that contribute to global warming according to the IPCC Fifth Assessment Report (AR5), and by converting them into CO_2 equivalent (by using the characterisation factors provided by the report). Land Use is intended as the area of land occupied by the power plant or installation. For hydropower, this doesn't include the occupation of water bodies. Since land use is not

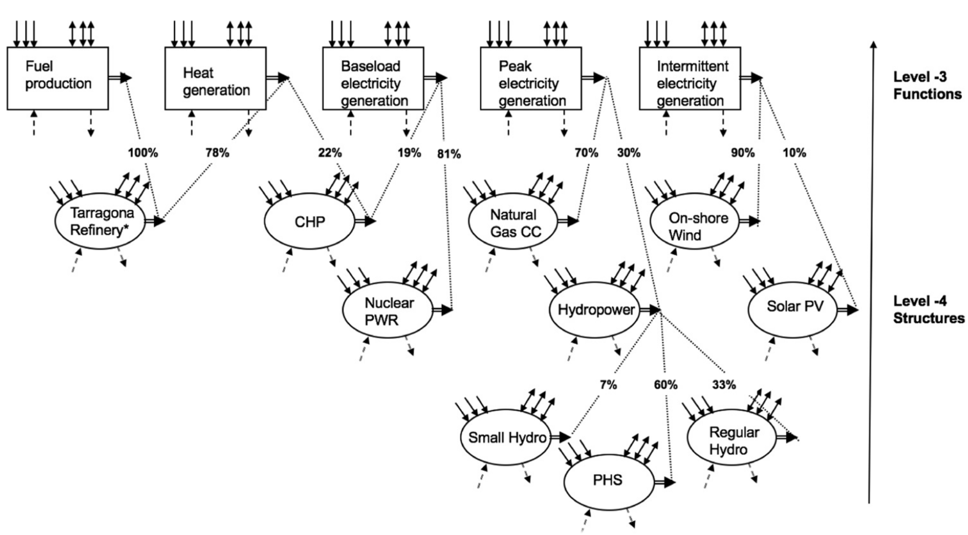

Fig. 4. Functional aggregation of electricity production processors.

discounted over the life of the processes, as the analysis has a yearly timescale, it is negligible for production of fuels and electricity (apart from renewables), as the majority of land used in the energy sector is during mining and extraction operations, and for the production of crops for biofuels. The choice of what to include in the processor and how to define its inputs and outputs is not fixed. Moreover, definitions can be tailored depending on the goal of the analysis and on who the information is being produced for (or with).

To compare and aggregate processors, all inputs are intensive, scaled by the main output – in this case, GWh of electricity for power plants and TJ of fuels for refineries. In this way, each process is described in relative terms (as a unitary operation). This kind of abstraction is useful in order to compare processes, for example to see which type of power plant consumes more water per GWh produced. However, in this framework, representations referring to unitary operations are also scaled in terms of absolute values, in order to contextualise them. This is where the functionality of different elements comes into play: a certain process may take up less land than others, but also produce a different type of energy carrier which is, in turn, used differently by a societal compartment to perform a specific task. This duality between the need for both intensive values referring to typologies and the need for extensive values contextualised to specific instances of energy systems is central to our approach. In this way, two non-equivalent descriptions of the system are considered simultaneously.

The production of intensive descriptions of inputs and outputs becomes problematic for co-generation processes, where the same profile of inputs refers to a profile of outputs. In our case this occurs in CHP and refinement. To avoid allocation, a pattern of fixed output ratios is associated with the typology. There are limits to this kind of simplification, but by avoiding allocation methods, the inherent entanglement of patterns is explicitly addressed.

Table 3 shows an example of intensive data for the processor "On shore wind power", where only four inputs are relevant. Similar tables are collected for each structural processor and are included in the Appendix. Then, a functional grouping of structural processors is performed, aggregating them based on the functionality of their outputs, and moving up the hierarchy (Fig. 4). For electricity, three functions are identified: production of baseload electricity, production of peak electricity, and production of intermittent electricity. These three types of electricity generation are well-known in engineering, where they are often split into further sub-categories such as middle-load (or load-following). However, in broader energy studies the distinction is rarely made – see, for example, some of the 100% renewable energy studies published over the past decade, where all electricity is referred to as being the same (Jacobson et al., 2015; Williams and Meisen, 2011; Mason et al., 2010; Lund and Mathiesen, 2009). While physically (i.e. structurally) all electricity is indeed the same, being a flow of electric charge, it "usefuleness for society" depends on how, when and where it is generated and how, when and where it is used.

Breaking down the electricity production curve into baseload and peak production allows us to comment on the role of renewables: since the electricity generated from renewable sources is outside human control, it cannot be channelled into a desired function of baseload or peak production. This is why a third processor of "intermittent generation" is included in the analysis, as technologies relying on intermittent sources have different metabolic characteristics than others, as well as different functionalities. Intermittent electricity can become functionally equivalent to either baseload or peak electricity when paired with storage technologies or back-up infrastructure, or both, by increasing grid flexibility (Denholm and Hand, 2011; Steinke et al., 2013).

Aggregating electricity generation into functional groups allows comparing the differences in types of electricity generation, by building intensive functional

processors – a quantitative description of the functional group. Table 4 shows how, for the same GWh of baseload, peak and intermittent power produced in Catalonia, a different pattern of flows and funds is needed.[7]

Some descriptive comments in relation to the nexus can be made: the production of a GWh of baseload electricity in Catalonia requires double the amount of electricity than for peak and intermittent outputs; baseload electricity also requires a higher labour input than peak electricity, however not higher than intermittent at 151 h per GWh produced. Water consumption is highest for peak electricity (more than double what is needed for baseload), as well as GHG emissions, while the only type of electricity generation with a substantial land use requirement is intermittent, at 11 ha per GWh. These descriptive results may acquire value when contextualised in relation to policy questions.

As mentioned previously, a combination of intensive and extensive representations of nexus patterns, i.e. abstracted unitary representations and representations contextualised in relation to their size, is useful to understand the behaviour of the energy system. Therefore, Table 5 includes inputs and outputs for functional electricity generation groups, this time in an extensive format. This shows how, for example, intermittent electricity consume more human activity per GWh produced than the other two types, but in extensive terms they are the sector which employs less human activity. The analysis for heat and fuels is simpler for this case study, as the functional groups are not split into further sub-functions. Table 6 shows the set of inputs and outputs associated to the refinery process.[8]

Having described the patterns of inputs and outputs required for the production of electricity, heat and fuels, these can be aggregated into a final pattern required for the whole energy sector, in what is represented as an *energy sector processor* (Fig. 5 and Table 7). This processor reflects data which can be, in some cases, available from statistical bodies, although often not to this grain of detail. However, obtaining the set of data from bottom-up aggregation is key in understanding the sets of different mechanisms and functionalities that have to be considered to explain the observed final pattern, and to build scenarios. A sound understanding of the underlying metabolism leading to the final behaviour of the energy sector is useful if one wants to modify such pattern, for example with the aim of reducing emissions or water use, while also understanding the effect that changes may have on different nexus patterns at different levels. Table 7 represents the various inputs and outputs of the energy sector. The data in this case is extensive rather than intensive, therefore it is obtained by summing the extensive data of the three functional processors below it. The first

Table 3
Structural processor (intensive) for "On shore wind power" Level −4.

Type: On-shore wind power

Details	Label		Unit	Source
Internal flow input	Electricity	22	MWh/GWh	ICAEN (2012)
Internal flow input	Fuels	0	GJ/GWh	–
External flow input	Water	0	m^3/GWh	–
Internal fund input	Human Activity	120	h/GWh	Budia et al. (2013)
Internal fund input	Power Capacity	470	kW/GWh	ICAEN, (2012)
External fund input	Land Use	12	ha/GWh	Budia et al. (2013)
External flow output	GHG emissions	0	t CO2 eq./GWh	–

[7] This only includes "electricity generation", and a full characterisation of the differences would have to include further steps in the energy chain (the full sequential pathway).

[8] The inputs and outputs associated to the production of heat through CHP and of heating fuels for refinery processes are accounted for in the structural processors of CHP and of the refinery, therefore a separate accounting is not necessary.

Table 4
Comparison of intensive processors for baseload, peak and intermittent electricity Level −3.

Details	Label	Unit	Baseload	Peak	Intermittent
Internal flow input	Electricity	MWh/GWh	42	23	20
Internal flow input	Fuels[a]	GJ/GWh	216	0	0
External flow input	Water	m^3/GWh	161	474	0
Internal fund input	Human Activity (HA)	h/GWh	111	57	151
Internal fund input	Power Capacity (PC)	kW/GWh	140	544	504
External fund input	Land Use (LU)	ha/GWh	0	0	11
External flow output	GHG emissions	t CO_2 eq./GWh	69	321	0

[a] Fuels do not include the primary energy source, e.g. Uranium for PWR or natural gas for CHP.

Table 5
Comparison of extensive inputs and outputs for functional electricity generation groups, and their relative share of the total Level −3.

Label	Unit	Baseload (66%[a])	%	Peak (27%[b])	%	Intermittent (7%[c])	%	Total
Electricity	GWh	1.26E + 03	79	2.71E + 02	17	6.00E + 01	4	1.59E + 03
Fuels	TJ	6.41E + 03	100	0.00E + 00	0	0.00E + 00	0	6.41E + 03
Water	10^3 m^3	4.79E + 03	46	5.69E + 03	54	0.00E + 00	0	1.05E + 04
Human Activity (HA)	10^3 h	3.29E + 03	74	6.86E + 02	15	4.51E + 02	10	4.43E + 03
Power Capacity (PC)	MW	4.15E + 03	34	6.53E + 03	54	1.50E + 03	12	1.22E + 04
Land Use (LU)	ha	1.81E + 02	1	2.37E + 02	1	3.31E + 04	99	3.35E + 04
GHG emissions	t CO_2 eq.	2.06E + 03	35	3.85E + 03	65	0.00E + 00	0	5.91E + 03

[a,b,c] The percentage given in brackets is in relation to the contribution of each functional group to Catalonia's total electricity production.

Table 6
Extensive and intensive inputs and outputs of the refinery process.
Source: PRTR Level −4.

Details	Label	Unit intensive	Value intensive	Unit extensive	Value extensive
Internal flow input	Electricity	GWh/TJ	8.27E − 01	GWh	4.36E + 02
Internal flow input	Fuels	GJ/TJ	4.00E + 00	TJ	1.86E + 03
External flow input	Water	m^3/TJ	1.40E + 01	m3	7.40E + 06
Internal fund input	Human Activity	h/TJ	4.00E + 00	h	1.95E + 06
External fund input	Land Use	ha/TJ	8.00E − 04	ha	4.43E + 02
External flow output	GHG emissions	t CO2 eq./TJ	4.00E + 00	t CO2 eq.	2.32E + 06
Internal flow output	Total refinery output			TJ	5.27E + 05

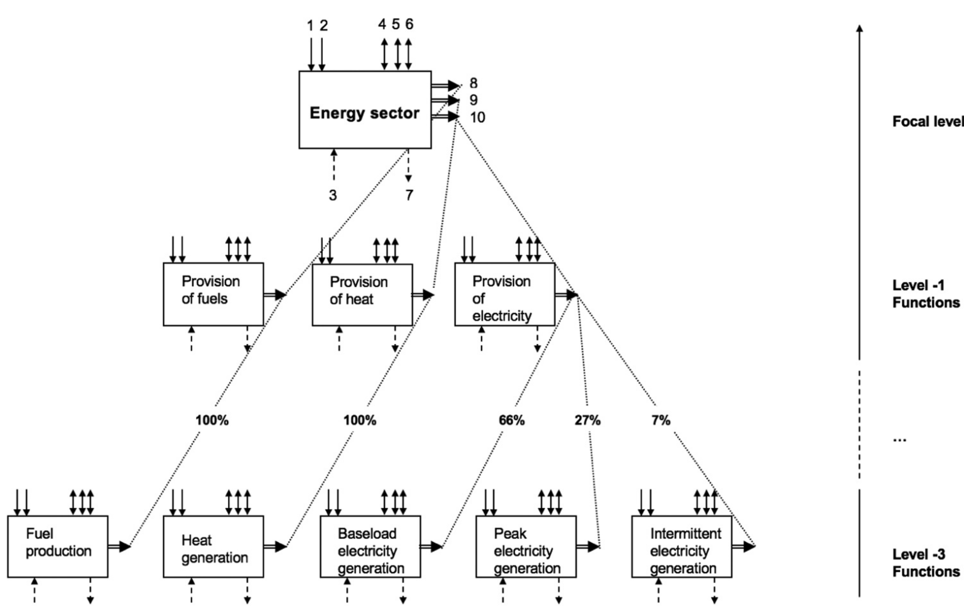

Fig. 5. Energy processor.

Table 7
Data for energy sector processor (including only generation of heat, fuels and electricity) Focal level.

# on Fig. 5	Details	Label	Unit	Value
1	Internal flow input	Electricity	GWh	2.03E + 03
2	Internal flow input	Fuels	TJ	8.27E + 03
3	External flow input	Water	10^3 m^3	1.79E + 04
4	Internal fund input	Human Activity (HA)	10^3 h	6.38E + 03
5	Internal fund input	Power Capacity (PC)	MW	1.22E + 04
6	External fund input	Land Use (LU)	ha	3.39E + 04
7	External flow output	GHG emissions	t CO_2 eq.	2.33E + 06
8	Internal flow output	Electricity	GWh	4.67E + 04
9	Internal flow output	Fuels	TJ	3.06E + 05
10	Internal flow output	Heat	TJ	1.37E + 05

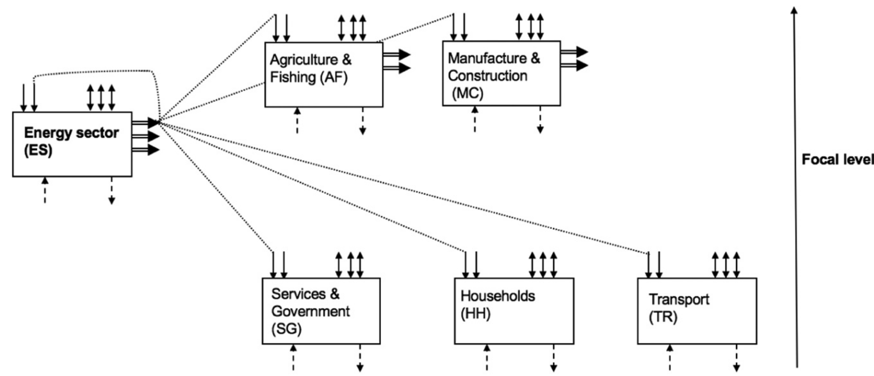

Fig. 6. Link between energy processor and end uses.

column of the table represents the labels shown in the energy sector processor of Fig. 5.

5.2. End uses: linking production to consumption

The internal flow outputs, finally, can be allocated to different sectors of society. Since part of what the energy sector produces is also consumed within the sector itself, the representation linking the energy sector processor to End Uses (Fig. 6) shows this loop.

For simplicity, only one loop back into the energy sector is represented in Fig. 6, while Table 8 shows how each energy carrier flow is consumed by different parts of society, including the energy sector.

5.3. Model validation and uncertainty

By aggregating bottom-up data into a higher level description, the congruence between different sources of data can be checked. This is a method often used by experts in their own operations, but rarely performed in formal modelling since different types of data tend to be used for different types of analyses. In our framework, there is a forced relationship across levels, as the outputs of functional types, aggregated from technologies, must equal the inputs into end uses (taking into account, of course, of trade and losses). This allows for a quality check of the coherence of the data across levels.

Comparing the aggregated description of Catalonia's energy sector to top-down statistics, we see how the data presents some discrepancies (Table 9). We have not considered all steps of the energy sector, therefore it is expected for the aggregated bottom-up data to have lower values than the statistical ones, as the table shows. Moreover, data specific to the energy sector is rarely available through statistical bodies, as it is usually aggregated with other sectors such as industry. However, for values where data were available, bottom-up estimations fell within the right order of magnitude. In general, discrepancies between aggregated and statistical data may be due to three types of inconsistencies: (i) in the quality of statistical data; (ii) in the quality of bottom-up data; (iii) in the scaling relations moving from bottom-up to top-down data. Further analyses of this kind could be used to discern trends in the inconsistencies, and determine the sources of error, flagging possible systematic errors in statistical bodies.

A hierarchical organisation of the information characterising energy systems also allows us to open up a discussion on uncertainty. Looking back at Fig. 4, uncertainty may arise across different levels: there is uncertainty in the inputs and outputs depending on the uncertainty in data sources and on the level of aggregation; moving up, uncertainties are associated to the combination of structural groups into functional ones; at the level of end uses, there is uncertainty in how many energy

Table 8
End uses Level 1.

	Baseload electricity (GWh)	Peak electricity (GWh)	Intermittent electricity (GWh)	Fuels (TJ)	Heat (TJ)
Energy sector (ES)	1760	100	100	8010[a]	57,800
Agriculture & Fishing (AF)	370	20	10	12,390	5320
Manufacture & Construction (MC)	14,880	1160	500	9640	85,080
Services & Government (SG)	7360	5880	1470	9300	13,940
Households (HH)	5330	4260	1070	10,430	41,620
Transport (TR)[b]	900	70	30	2,277,720	0

[a] data on fuel consumption of the energy sector does not include PES.
[b] includes consumption of passenger vehicles.

Table 9
Comparison between aggregated data, and data obtained through statistical offices, for Catalonia in 2012. *Focal level.*

Catalonia's energy sector, 2012	Unit	Aggregated	Statistical	Source	% difference
GHG emissions	t CO2 eq.	2.330E + 06	6.502E + 06	ICAEN	64
Water consumption	10^3 m^3	1.790E + 04	N/A[a]		
Labour	10^3 h	6.380E + 03	N/A[a]		
Electricity consumption	GWh	2.030E + 03	2.477E + 03	ICAEN	18
Fuels consumption	TJ	8.270E + 03	1.829E + 04	ICAEN	55
Land use	ha	3.390E + 04	N/A[a]		

[a] Catalan government statistics do not disaggregate to this level of detail.

carriers are consumed per sector, especially upon further disaggregation of electricity into baseload, peak and intermittent. The more we develop a diversified characterisation of the expected relations over the data, the more we can reduce the number of *known unknowns* (Knight, 1921) relevant to the analysis.

5.4. Policy relevance

The strength and novelty of this energy model lie in its ability to facilitate informed discussions with stakeholders on policy relevant issues. The hierarchical mapping from primary energy sources, to the technologies harnessing them, to their function in society may help in guiding discussions of energy futures. The model carries a manageable amount of information across different domains, which can be compressed or expanded depending on the policy question to be discussed. Table 7 shows, for example, how the Manufacturing & Construction sector in Catalonia is the one consuming the highest amount of baseload electricity – this is because industries tend to operate 24 hours a day, 365 days a year. Over 80% of baseload electricity, on the other hand, is produced by nuclear power (see Fig. 4). Therefore, when discussing a shift from nuclear power to renewable energy in Catalonia, it is important to consider the role that electricity from nuclear power plays in the industrial sector, and whether intermittent sources can be used to cover the same function, and if so at which social, capital (due to their low CUF) and biophysical cost – for example, what are the implications for land uses needed for the renewable infrastructure? At what cost can the grid become more flexible? On the other hand, the household sector has a high consumption of peak electricity, since demand in households varies throughout the day. In this case, flexible forms of demand-side management, integrated with intermittent generation, could be more successful.

Moreover, Table 7 shows how electricity and thermal energy (heat and fuels) are consumed differently by society. Structural changes can partially be used to interchange the two, for example by using electric vehicles to reduce fuel consumption in the transport sector. However, not all functions covered by thermal energy can be replaced by electricity – a further disaggregation of end uses into specific processes could show, for example, how many of the fuels consumed in the transport sector are for road vehicles and how many are for navigation and aviation, where electricity may not be a suitable substitute. In the Manufacturing & Construction sector, similarly, some processes such as smelting furnaces used to make iron require a thermal input which renewable sources struggle to provide. Trade-offs across levels may also emerge: a technological change, such as switching to a power plant consuming less water per output, may have positive effects on local ecosystems but produce unwanted effects on nexus patterns at higher hierarchical levels, or be constrained by which changes are perceived to be desirable at the level of end uses.

These examples show how the recognition of the importance of functionality and its inclusion in the hierarchical organisation of the model is useful in informing policy questions across nexus domains. In OECD countries the energy sector can be seen as having the overall function of *providing a supply of energy matching demand at all times*. This expectation imposes local functions on its sub-components arranged to fulfil the sector's higher purpose, which in turn is aligned with functions at the societal level (what the energy is used for in different economic compartments of society). By making this function explicit, it may become contested.

6. Conclusions

Ludwig and Walters (1985) have argued that simplified models are more effective than large complex ones for policy decisions. On the other hand, the wisdom of Box (1979) reminds us that, “all models are wrong, but some are useful”. Simple and effective models, rather than simplistic ones, are needed to deal with complex sustainability challenges. Iwasa et al. (1987) suggest that, in order to simplify complex systems, attention should be turned to “techniques for choosing appropriate levels of aggregation”. This observation resonates with the point made in the Introduction of this paper: when dealing with the analysis of complex systems operating across different levels of organisation, their characteristics can only be observed by adopting different scales. Thus, the quality of a representation based on a quantitative assessment depends on the ability of integrating non-reducible observations.

The energy model introduced in this paper proposes a technique to choose appropriate levels of aggregation in the complex energy system, based on the grouping of structural elements into functional ones. In this way, the hierarchical organisation of energy systems is used to simplify their representation and their relation to other nexus elements, while avoiding an excessive loss of relevant information. The strength of the model lies across two domains. The first is in the domain of energetics, contributing to a shift in the field towards interdisciplinarity, by describing functional elements of the energy system through nexus patterns. Secondly, at the science-policy interface, the model may be used as a heuristic tool to inform decision-making, moving away from a paradigm of science speaking truth to power, and towards the co-production of knowledge among scientists, policymakers and other stakeholders.

Acknowledgments

The authors gratefully acknowledge research funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 689669 (MAGIC). The Institute of Environmental Science and Technology (ICTA) has received financial support from the Spanish Ministry of Economy and Competitiveness, through the “María de Maeztu” program for Units of Excellence (MDM-2015-0552). This work reflects the authors’ view only; the funding agencies are not responsible for any use that may be made of the information it contains.

Appendix A

Table A.1
Structural Processors Level −4.

Details	Label	Value	Unit	Source
Type: Nuclear PWR				
Internal flow input	Electricity	45	MWh/GWh	ICAEN (2012, n.d.)
Internal flow input	Fuels	90	GJ/GWh	Diaz-Maurin and Giampietro (2013)
External flow input	Water	50	m^3/GWh	ANAV (2012)
Internal fund input	Human Activity	65	h/GWh	ANAV (2012)
Internal fund input	Power Capacity	131	kW/GWh	ICAEN (2012, n.d)
External fund input	Land Use	0.004	ha/GWh	NEI (2015)
External flow output	GHG emissions	0	–	–
Type: Natural Gas Combined Cycle (CC)				
Internal flow input	Electricity	26	MWh/GWh	ICAEN (2012, n.d.)
Internal flow input	Fuels	0	GJ/GWh	PRTR, n.d.
External flow input	Water	650	m^3/GWh	Dones et al. (2007)
Internal fund input	Human Activity	61	h/GWh	
Internal fund input	Power Capacity	493	kW/GWh	ICAEN (2012, n.d.)
External fund input	Land Use	0.022	ha/GWh	NEI (2015)
External flow output	GHG emissions	460	t CO_2 eq./GWh	Dones et al. (2007)
Type: Combined Heat & Power (CHP)				
Internal flow input	Electricity	33	MWh/GWh	ICAEN (2012, n.d.)
Internal flow input	Fuels	748	GJ/GWh	ICAEN (2012, n.d.)
External flow input	Water	630	m^3/GWh	Dones et al. (2007)
Internal fund input	Human Activity	305	h/GWh	ACOGEN (2010a)
Internal fund input	Power Capacity	178	kW/GWh	ICAEN (2012, n.d.)
External fund input	Land Use	0.015	ha/GWh	ACOGEN (2010b)
External flow output	GHG emissions	363	t CO_2 eq./GWh	Dones et al. (2007)
Type: Small hydro (< 1 MW)				
Internal flow input	Electricity	14	MWh/GWh	ICAEN (2012, n.d.)
Internal flow input	Fuels	0	GJ/GWh	Flury and Frischknecht (2012)
External flow input	Water	0	m^3/GWh	Flury and Frischknecht (2012)
Internal fund input	Human Activity	25	h/GWh	Benchmark from private communication with an engineer working at Endesa
Internal fund input	Power Capacity	355	kW/GWh	ICAEN (2012, n.d.)
External fund input	Land Use	0.006	ha/GWh	Dones et al. (2007)
External flow output	GHG emissions	0	t CO_2 eq./GWh	Dones et al. (2007)
Type: Regular hydro (> 5 MW)				
Internal flow input	Electricity	145	MWh/GWh	ICAEN (2012, n.d.)
Internal flow input	Fuels	0	GJ/GWh	Flury and Frischknecht (2012)
External flow input	Water	29	m^3/GWh	Dones et al. (2007)
Internal fund input	Human Activity	50	h/GWh	Benchmark from private communication with an engineer working at Endesa
Internal fund input	Power Capacity	760	kW/GWh	ICAEN (2012, n.d.)
External fund input	Land Use	0.023	ha/GWh	Dones et al. (2007)
External flow output	GHG emissions	0.4	t CO_2 eq./GWh	Dones et al. (2007)
Type: Pumped hydro storage (PHS)				
Internal flow input	Electricity	145	MWh/GWh	ICAEN (2012, n.d.)
Internal flow input	Fuels	0	GJ/GWh	Flury and Frischknecht (2012)
External flow input	Water	160	m^3/GWh	Dones et al. (2007)
Internal fund input	Human Activity	50	h/GWh	Benchmark from private communication with an engineer working at Endesa
Internal fund input	Power Capacity	550	kW/GWh	ICAEN (2012, n.d.)
External fund input	Land Use	0.026	ha/GWh	Dones et al. (2007)
External flow output	GHG emissions	0.4	t CO_2 eq./GWh	Dones et al. (2007)
Type: On-shore wind power				
Internal flow input	Electricity	22	MWh/GWh	ICAEN (2012, n.d.)
Internal flow input	Fuels	0	GJ/GWh	–
External flow input	Water	0	m^3/GWh	–
Internal fund input	Human Activity	120	h/GWh	Budia et al. (2013)
Internal fund input	Power Capacity	468	kW/GWh	ICAEN (2012, n.d.)
External fund input	Land Use	12	ha/GWh	Budia et al. (2013)
External flow output	GHG emissions	0	t CO_2 eq./GWh	–
Type: Solar PV				
Internal flow input	Electricity	0	MWh/GWh	ICAEN (2012, n.d.)
Internal flow input	Fuels	0	GJ/GWh	–
External flow input	Water	0	m^3/GWh	–
Internal fund input	Human Activity	440	h/GWh	APPA (2012)
Internal fund input	Power Capacity	856	kW/GWh	ICAEN (2012, n.d.)
External fund input	Land Use	3	ha/GWh	APPA (2012)
External flow output	GHG emissions	0	t CO_2 eq./GWh	–
Tarragona Refinery				
Internal flow input	Electricity	0.8	MWh/TJ	PRTR, n.d.
Internal flow input	Fuels	4	GJ/TJ	PRTR, n.d.
External flow input	Water	14	m^3/TJ	PRTR, n.d.

(continued on next page)

Table A.1 (*continued*)

Details	Label	Value	Unit	Source
Internal fund input	Human Activity	4	h/TJ	PRTR, n.d.
Internal fund input	Power Capacity	N/A	kW/TJ	PRTR, n.d.
External fund input	Land Use	0.000841	ha/TJ	PRTR, n.d.
External flow output	GHG emissions	4410	t CO_2 eq./TJ	PRTR, n.d.

Note: "Water" is intended here as water consumed or evaporated throughout the process (not water throughput that is then released); Inputs and outputs scaled per GWh of CHP also have a corresponding fixed pattern of heat being generated; Inputs and outputs scaled per TJ in the refinery refer to TJ of total products (fuels + heat + other products).

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