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Implications for science and for policy

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Ph.D. dissertation

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Cover: "We are so much more than the sum of our parts", Louisa Jane Di Felice (2020)

In memory of Alix

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Abstract

This thesis investigates the implications of complexity for the production of models of social-ecological systems and for the science-policy interface. I focus on energy policy in the European Union (EU), through case studies developed within the Horizon 2020 project MAGIC.

The theory of complexity is broad and multi-faceted. It may take different forms depending on who invokes it and in what context – perhaps a consequence not only of its newness and of its interdisciplinary standing, but also of the complexity of the theory itself. The way I refer to complexity builds on the work of Robert Rosen, who defined a complex system as one which can be described in non-equivalent and non-reducible ways. This powerful definition, which I refer to as Rosennian (or relational) complexity, calls for deep reflections on the way scientific knowledge is used to inform our image of the world and how we act upon that image. It focuses on the role played by observers in perceiving systems and in modelling them, through devices that I refer to as narratives. Narratives allow reducing the information space of complex reality into a manageable storyline which can be used to guide action, establishing causal patterns across impredicative processes operating at different scales. As such, they are central both to science and to policymaking. Narratives cannot be true or false, only adequate or obsolete with respect to the perception of a system.

Through a series of case studies, I develop the tools needed to describe energy systems across multiple scales, question whether narratives underpinning EU energy policy are adequate in addressing their concerns and inspect the role played by academia in shaping those narratives. The methodological implications of modelling energy systems at the science-policy interface are addressed through a case study of Catalonia's energy sector. Building on hierarchy theory, the region's energy system is described in structural terms and in functional ones, showing how a functional description is useful in guiding policy questions. By mapping nexus dimensions across hierarchical levels, this first case study provides the tools to generate nexus assessments in open and transparent ways. In the second case study, a collaboration with Zora Kovacic, I focus on energy security, one of the pillars of the EU's Energy Union. Inspecting the multiple definitions and dimensions connected with energy security in the academic literature, we argue that the ambiguity of the term is functional in policymaking and is not a matter to be solved with increased definitional clarity. Rather, ambiguity is embedded in complexity. This suggests that the production of definitions and indicators of energy security in academia may not be useful to policy. The third case study analyses the narratives surrounding electric vehicles in the EU. Policy narratives in EU documents are identified through a text analysis and mapped across hierarchical levels. A taxonomy to classify policy narratives is introduced, making the distinction between normative narratives (defining *what* is a desirable policy solution), justification narratives (defining *why* it is desirable) and explanation narratives (defining *how* it should be implemented). Through a review of existing studies and reports, the quality of the constellation of narratives surrounding electric vehicles is inspected, focusing on the relationship between normative and justification narratives. Results show how this relationship is uncertain at best. Focusing on the role played by science in informing policy, they point to the need of recognising the way in which policy narratives affect and are affected by academic ones. The fourth and most recent case study is an expansion of the first one, presented here as exploratory work in progress. The energy metabolisms of Spain, Sweden and the EU are described through holarchies, including each branch of the energy system (electricity, heat, gas and fuels). This multi-scale mapping is used to discuss two issues that are central to EU energy policy: decarbonisation and externalisation. I question EU decarbonisation narratives and highlight uncomfortable knowledge regarding the reliance of the EU's energy sector on imports. A database of nexus inputs and outputs associated with each energy process is provided as a central output of this study, in the hope that it will be useful to researchers wanting to generate integrated nexus assessments in support of energy governance.

Taken together, these case studies provide insights across three domains. First, there is a methodological contribution, as I develop the tools needed to carry out nexus assessments at multiple levels. Second, I contribute to the knowledge base regarding EU sustainability challenges and their related policies. The four case studies address decarbonisation, energy security, electric vehicles and externalisation. Third, I contribute to the growing debate on adaptive governance in complexity. With this respect, I do not provide concrete guidance. Rather, the four case studies serve as examples which can be used to think about adaptive governance through the lens of complexity, leading to a series of insights and reflections.

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Contents

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Acronyms

BCNDC: Baconian/Cartesian/Netwonian/Darwinian/Comtean
BM: biosphere matrix
CAP: Common Agricultural Policy
CC: combined cycle
CEAE: Clean Energy for All Europeans
CHP: combined heat and power
CLEWS: Climate, Land, Energy and Water Strategies
CUF: capacity utilisation factor
EC: energy carrier
ECB: European Central Bank
EJAtlas: Environmental Justice Atlas
EU: European Union
EURS2016: EU Reference Scenario 2016
EV: electric vehicle
GDP: gross domestic product
IAM: integrated assessment model
ICAEN: Catalan Institute of Energy
ICEVs: internal combustion engine vehicles
IMAGE: Integrated Model to Assess the Global Environment
IPCC: Intergovernmental Panel on Climate Change
GHG: greenhouse gases
LU: land use
MAGIC: Moving Towards Adaptive Governance in Complexity
MUSIASEM: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism
PC: power capacity
PES: primary energy source
PHS: pumped hydropower storage
PNS: Post-Normal Science
PV: photovoltaics
PWR: pressurised water reactor
QE: quantitative easing
QST: quantitative storytelling
SES: social-ecological system
TM: technosphere matrix
US: United States
WEAP: Water, Energy and Planning
WELMM: Water Energy Land Materials and Manpower

Chapter 1

Introduction

Much of complex systems science focuses, as the name suggests, on complexity as a property attributed to certain systems. While there is little agreement on an exact compendium of properties that is considered *enough* for a system to be complex, common ones include non-linearity, emergence, self-organization, multi-scalarity, and the fact that the system as a whole is different from the sum of its parts (Andersen, 1972). This is in contrast with the Cartesian view of science, where wholes can be seamlessly broken down into their components. While useful for many applications, an ontological understanding of complexity, viewing complex systems as something "out there" which can be studied and defined, fails to account for the role played by observers, often reducing complexity to a material property. A different type of complexity, focused on the observer-observation complex, has been the basis for Allen and Starr's Hierarchy Theory (Allen and Starr, 1982) and has been explored by Giampietro et al., (2006) and Allen et al., (2017), among others. In their view, complexity is not a property of reality per se, but arises from the interactions between observers and systems. This thesis builds on that stance, referring to it as relational, or Rosennian, complexity. According to the biologist Robert Rosen, complex systems are nonsimulable ones, in the sense that they can be described in non-equivalent and non-reducible ways (Rosen, 1958).

Relational complexity is not only about observers existing, but also about observers and observations co-evolving (often at different paces) and affecting one another. This makes the epistemology of complexity a question of knowledge *in* complexity, rather than one of knowledge *of* complexity (Strand, 2002; Giampietro et al., 2006). It also makes the question of an ontology of complexity tangential, if not senseless: if complexity arises from the interaction between systems and observers, there is no way to discuss the ontic properties of complex systems, as any behaviour is the necessary result of pre-analytical, and analytical, choices of observation. Thus, similar to Allen et al. (2017), throughout this thesis I remain agnostic to the ontology of complexity.

In the relational view of complexity, narratives play a central role. In complex realities, multiple events across different scales affect one another, through impredicative loops. There is no absolute direction of causality across scales, but only causal storylines that are built following the observers' priorities and points of view. Narratives are devices used by observers to reduce the information space of the world into a manageable and self-consistent set of observations which can be used to guide action. As such, they underpin both scientific modelling and policymaking.

Policies are built on narratives defining what is relevant, why it is relevant, and how to guide actions in relation to those relevant issues. In building formal models of the world, science also relies on a set of choices defining what is relevant (what I refer to as pre-analytical choices) and a set of choices defining how to study it (what I refer to as analytical choices). Sustainability science, in particular, is a relatively new field that is simultaneously dealing with a set of interconnected and urgent issues across multiple temporal and spatial scales. Among the many issues it faces, the science lacks methodological tools which can be used to grasp the complexity of the relations it analyses, and the uncertainties that this complexity brings (Giampietro et al., 2014). I argue that a grounding in Rosennian complexity can contribute to the maturing of sustainability science. This, in turn, can be part of a shift from the Cartesian model of science as a tool for prediction and control, to the complexity model of science as a tool for exploration, deliberation and co-production of trusted knowledge claims.

Applying this relational view of complexity to EU energy policy, I ask: Are narratives underpinning EU energy policy obsolete? What is the mutual relationship between policy narratives and scientific knowledge? And how can scientific models accommodate multiple scales and views of energy systems?

This first chapter offers some background to better understand the chosen case studies presented in Chapters 2-5. Background is offered in terms of information on EU energy policy and its guiding principles, and in terms of the field of complexity, with a focus on the branches that I build on and contribute to. In Section 1.1, I outline the principles of EU energy policy and the interconnected sustainability challenges faced by the EU. While case-specific, the underlying principles of these challenges emerge in the energy governance of all countries in the Global North and are inherently connected to the challenges faced in the Global South, both materially and politically. Section 1.1 also provides an overview of how knowledge is filtered at the EU science-policy interface, justifying the need for integrated nexus assessments in informing complex sustainability challenges. Here, I introduce the MAGIC project (MAGIC Nexus Project, 2018), which has funded my research for the past four years. Section 1.2 summarizes the theoretical frameworks on which my results stand, and to which they contribute. I start by providing a broad, and necessarily limited, overview of the field of complexity, directing readers to relevant work. I then describe, to a higher level of detail, the branches of complexity which this work heavily draws from, namely hierarchy theory and societal metabolism (the second being grounded in the first). Section 1.2 ends by discussing the role played by complexity in policy and decision-making, introducing the authors and thoughts which have inspired much of my own work. I end this chapter with an outline of my research questions (Section 1.3), connecting each one to the results presented in subsequent chapters.

1.1. Motivation

1.1.1. Energy policy in the EU

"The atmosphere is warming and the climate is changing with each passing year. One million of the eight million species on the planet are at risk of being lost. Forests and oceans are being polluted and destroyed. The European Green Deal is a response to these challenges. It is a new growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use." (EC, 2019a, p.2)

The first paragraph of the Communication on the European Green Deal summarizes the underlying discourse of EU sustainability policy. Local and global environmental concerns are painted in an urgent light: climate change, biodiversity loss and a rise in pollution threaten life on earth. In response to these challenges, what the European Commission (EC) proposes is a *growth strategy* (re-labelled in the subsequent amendment proposal as a *sustainable growth strategy* (EC, 2020a)). Under the paradigm of (sustainable) economic growth, the futures of three domains are envisioned. First, society itself is to be fair and prosperous. Second, the economy is to be modern, resource-efficient and competitive. Third, there are to be no greenhouse gas (GHG) emissions. Thus, society, the economy and the environment are the three entities to be protected. The wellbeing of each entity is viewed as complementary to the others': specifically, economic growth and resource use will be decoupled by 2050, ensuring that an increasingly growing economy will not lead to environmental degradation. Within this framing of priorities and concerns, EU policies related to sustainability (what I refer to as "EU sustainability policies", which is not an official term used by the EC) are organised under different branches, including energy policy, food policy (namely the CAP) and transport policy. This thesis focuses on energy policy, while also touching upon transport policy, and always viewing energy through a nexus perspective which links it to other sustainability domains.

EU energy policy is centred around four directives: on the energy performance of buildings (EC, 2018a), on common rules for the internal market for electricity (EC, 2019b), on the promotion of the use of energy from renewable sources (EC, 2018b) and on energy efficiency (EC, 2018c). These four directives are collected under the 2018 Clean Energy for All Europeans (CEAE) Package, also known as the Winter Package. The CEAE package, in turn, is part of the EU's broader Energy Union strategy, which was launched in 2015. The Energy Union strategy "(…) as a key priority of the Juncker Commission (2014-2019), aims at building an energy union that gives EU consumers – households and businesses – secure, sustainable, competitive and affordable energy" (EC, 2020b). It is built around five pillars: security, solidarity and trust; a fully integrated internal energy market; energy efficiency; climate action, decarbonising the economy; research, innovation and competitiveness.

The CEAE package and its associated legislative acts are central to the EU's wider economic strategy. Clean energy is framed as a means to sustain economic growth, create jobs and strengthen the competitiveness of EU industry. When it comes to sustainability, environmental dimensions beyond a reduction of GHG emissions are lacking. Exceptions include issues of soil quality, sustainable forest management linked to the production of bioenergy, and the vague call for prudent and rational utilisation of natural energy resources. In terms of solutions, renewable energy and efficiency are the two key measures aimed at simultaneously boosting the economy and reducing GHG emissions. Of the three entities central to the European Green Deal (society, the economy and the environment), the economic component is the one that is most frequently stressed throughout EU energy directives, including the directives on renewable energy and on energy efficiency. According to the official EU storyline, renewable energy will generate employment, boost the European industry and its competitiveness, lead to sustainable economic growth and foster the development of local businesses, as well as the development of rural areas.

Similarly, efficiency measures are envisioned to have multiple positive effects on the economy, from generating new jobs to increasing economic competitiveness. Environmental and societal benefits are coupled to the central economic ones: as the economy improves, so will citizen's quality of life, while GHG emissions will inevitably be reduced, given the "green" nature of the proposed measures.

These policy storylines, where citizen wellbeing, economic growth and environmental benefits are positively coupled, leave little room for alternative sociotechnical imaginaries (Jasanoff and Kim, 2015). The dominant perception of a techno-optimist future is materialised through a set of tangible targets: a 30% increase in renewables and efficiency by 2030, and net zero emissions by 2050. However, perspectives grounded in complexity cast serious doubts on whether this dominant EU storyline of coupled society-environment-economy wellbeing is realistic under current paradigms and consumption patterns. Can resource use effectively be decoupled from GHG emissions? Is economic growth compatible with environmental protection? Is a shift to renewables by 2050 possible and will it lead to zero net emissions?

Existing research shows how each of these questions is associated with high levels of uncertainty. When it comes to decoupling, it is still unclear whether it is possible for economic growth to continue without grave material consequences. In particular, decoupling discourses ignore two key dimensions. The first is the issue of financialization of the economy. Financialization refers the increasing role played by the financial sector in the global economy. Since 2008, the European Central Bank (ECB) has been injecting money into the economy, as a means to fight against recession (what is known as quantitative easing (QE) (Hausken and Ncube, 2013). It is unclear whether QE policies have had any significant impact on GDP growth (Fawley and Neely, 2013). However, they have increasingly facilitated a process of financialization, with monetary flows becoming increasingly regulated (or, better, unregulated) by leading institutions, further detaching them from material reality. On this topic, empirical research by Kovacic et al. (2018) has shown that, while energy intensity (energy throughput per unit of GDP) in the EU has declined between 1993 and 2013, the financial intensity (financial assets per unit of income) has increased, particularly in the financial sector. This suggests that apparent decoupling may be a consequence of financialization, and not of improved production processes, as the official decoupling narrative would suggest. The second dimension which is wilfully ignored by decoupling discourses is the case of externalisation. Data used to prove that economic growth is increasingly decoupled from resource use and environmental impacts, ascribing these positive effects to better technology and to efficiency, do not account for the fact that the primary and secondary sectors have been mostly shifted to countries outside of the Global North. In a collaboration led by Maddalena Ripa we show how this is the case for the EU's energy sector, which relies on imports (Ripa et al., 2021).

GHG emissions of the sector increase significantly when accounting for the emissions associated with imported energy products. The externalisation of primary and secondary sectors of the economy does not only have implications in terms of shifting patterns of GHG emissions and environmental degradation, but also in terms of the coupled metabolisms of importing and exporting countries. By investing resources, including human time, in producing material outputs to be exported, Global South countries limit the share of resources which can be invested in the tertiary sector. This suggests that global poverty reduction cannot be achieved by simply "developing" countries in the Global South, as their metabolism is directly constrained by that of "developed" countries.

The third question, of whether a shift to renewables by 2050 is possible, and whether it will lead to zero net emissions, places itself within a heated academic debate which often resembles an ideological one. There are many studies available which model 100% renewable electricity scenarios for 2050 (see Pleßmann and Blechinger 2017; Bussar et al. 2016; Capros et al. 2014; Haller et al. 2012, among others). Others are more cautious and have questioned the feasibility of a rapid decarbonisation of the electricity sector (Renner and Giampietro 2020; Loftus et al. 2015; Smil 2016). Importantly, these studies focus on the electricity sector. A full shift to renewables would require using alternative, renewable fuels (such as biofuels) in the heat and fuel sectors. Decades of research on biofuels have shown how they are not a feasible large-scale solution (see Giampietro and Mayumi (2009) for a comprehensive overview, and Cadillo-Benalcazar et al. (2020) for a recent review on the quality of biofuel narratives in the EU). An alternative to biofuels is the electrification of the transport sector. I partially address concerns related to this in Chapter 4. These concerns include the availability of storage for intermittent electricity, and the social and environmental impacts of these storage solutions, especially those requiring lithium. The issue of timing is also central to decarbonisation discourses (Fouquet, 2016). Historically, energy transitions have taken considerably longer than the timeline proposed by the EU (Smil, 2010). Then again, climate change is a unique threat which may lead to a shift in these historical patterns. The existing doubts and uncertainties about whether a full decarbonisation of the economy is feasible by 2050 do not mean that renewables, or efficiency measures, are useless and should not be implemented. They do point, however, to serious concerns about the narratives underpinning sustainability discourses, especially the view that technological fixes will be enough, that current consumption patterns do not have to shift dramatically, and that economic growth and environmental protection can be simultaneously achieved.

While this thesis does not address all of these matters, it provides the methodological grounds to address them in an integrated way. Science has a part to play not only in how these questions are answered, but also in which questions are considered to be relevant in the first place. In this spirit, much of the content presented here aims at questioning the dominant framing of EU policy and at unveiling alternative framings. I consider this critical perspective to be necessary in a context where the production of science is increasingly driven by funding interests, leaving less and less space for re-thinking and re-framing over-arching storylines and priorities. To provide context for this critical perspective, the next section gives an overview of the existing dynamics between science and EU energy policy.

1.1.2. Science for policy

There are different levels at which scientific knowledge and advice can influence policymaking. At the lowest and most concrete level, models and scenarios are used to inform policy targets and to map their interconnections, providing scientific advice. At a more diffuse level, scientific knowledge may contribute to a shared culture, generating the context within which certain sociotechnical imaginaries become dominant over others. As defined by Jasanoff and Kim (2015), sociotechnical imaginaries refer to "collectively held and performed visions of desirable futures (…) animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology" (p. 25). These imaginaries of desirable futures, then, frame which measures are concretely agreed upon. Importantly, imaginaries are simultaneously shaped by existing measures. This leads to political, cultural and material lock-ins. The two levels are shown in Figure 1, where I introduce the term "epistemic box", which will appear again in Chapter 4. An epistemic box includes the (often unspoken) imaginaries underpinning policy discourses, their associated policy measures and the science used to inform them. Often, the imaginaries determining policy concerns and priorities are taken for granted, and what we see is their manifestation through legislative acts (highlighted in in Figure 1).

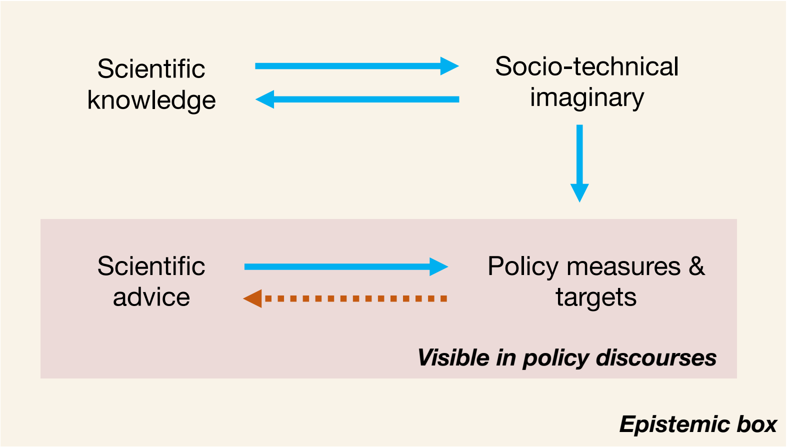

Figure 1. Influence of science on policy

Policy-based evidence refers to the case where science is used to support a pre-decided policy measure, rather than the other way around (Ravetz, 1971; Rayner, 2012; Saltelli and Giampietro, 2017). This is shown with a dotted arrow in Figure 1. This relationship is common when it comes to the models and scenarios informing EU energy policy. The EU Reference Scenario 2016 (EURS2016) depicts the interconnections between energy, transport and climate, and is the main analytical tool used to inform EU decision-makers, modelling trends up to the year 2050. The EUCO scenarios are an addition to the EURS2016, where specific targets for given years are modelled including, for example, efficiency and renewable targets. These models explore the effects of targets under different conditions and scenarios, rather than exploring alternatives that may question the targets themselves. Interestingly, the EURS2016 full report clearly states that the aim of the model is not one of prediction: "This report focuses on trend projections – not forecasts. It does not predict how the EU energy, transport and climate landscape will actually change in the future, but merely provides a model-derived simulation of one of its possible future states given certain conditions" (EC, 2016a, p.14). Despite moving away from predictive modelling, these scenarios still leave little space for exploration and contestation. This is not only due to the fact that policy measures are fixed to start with. It is also tied to how the models themselves are built and connected to one another.

In order to analyse the interactions across different sectors and domains, the EURS16 and EUCO scenarios concatenate the inputs and outputs of different macro-economic models, including the PRIMES energy model, the GEM-E3 environment-economy model, and the CAPRI agriculture model, among others. In this set-up, the nexus dimension is built as an added layer on top of each macro-economic model, rather than being embedded within each individual one. This view is deeply rooted in Cartesian science, as each part of the social-ecological system is broken down and modelled individually (e.g., land use, energy), with outputs then connected to one another. This ignores how changes at multiple levels of the social-ecological system can affect other dimensions. Beyond the issue of this reductionist view, the modelling codes used within each individual domain are often not available to the public. In Chapter 2, I address the implications of combining inputs and outputs of macro-economic, 'black-box' models, calling for integrated assessments that are open and interconnected at each step, and providing an alternative for how this may be done. The next section argues for the need to conduct nexus assessments in a way that recognises the complexity of social-ecological systems.

1.1.3. Nexus assessments and the need for complexity

As discussed in the previous section, integrated nexus assessments have yet to become commonplace at the EU science-policy interface, where domain-specific models are still the norm. One of the reasons for this may be that integrated nexus assessments inevitably highlight trade-offs, which are fundamentally against the win-win nature of EU sustainability policies. The lack of their implementation can also be attributed to the novelty of most of these approaches, as the nexus has only become a popular term over the last decade or so. The mainstreaming of the concept of the nexus can be attributed to the 2011 Bonn conference organized by the World Economic Forum Water Initiative, although the concept itself existed prior to 2011. Since its popularization, the nexus has been deeply tied to water assessments and water governance, as its early use was shorthand for the "water-energy" nexus. As a consequence, most early models on the nexus are centred around water use, such as the Climate, Land, Energy and Water strategies model (CLEWS).

With time, multiple dimensions have been added to the "water-energy" ones, and the term nexus has come to signify anything from water-energy-food, to also include terms such as environment, climate, biodiversity or land, depending on the context. When it comes to models simultaneously addressing multiple nexus dimensions, Keairns et al. (2016) provide a useful review, grouping nexus models under two categories: large-scale system models and life cycle and supply chain approaches. The work produced by my research group (the IASTE group based at ICTA[1]) is included in the former. This category includes other Integrated Assessment Models (IAMs) such as the Water Energy Land Materials and Manpower (WELMM), and the Integrated Model to Assess the Global Environment (IMAGE). These models analyse the interactions between nexus dimensions at the macro-scale, focusing on how these dimensions interact under long-term scenarios of changing production and consumption patterns. In Chapter 2, I discuss the differences between our approach and IAMs. Life cycle approaches, on the other hand, focus on the technological level, by providing inputs and outputs associated with different steps of production processes (at the micro-scale). The multi-scale approach developed in MAGIC and presented in this thesis aim to bridge these two levels. This is first introduced in Chapter 2 and then further expanded in Chapter 5, where I describe the energy sector of the EU from the micro-scale to the macro-scale, introducing an intermediate meso-scale level.

The popularization of the nexus does not only have implications for modelling, but also for the use of these modelling tools. Analysing UK debates on natural resources, Cairns and Krzywoszynska (2016) argue that the nexus has become a buzzword, meaning that it is simultaneously ambiguous and pregnant with normative values. They warn against the possible instrumentalization of the concept of the nexus as a means to push for a technocratic agenda, underpinned by a focus on technical solutions to environmental problems. To avoid the mobilisation of the nexus as a tool for the depoliticization of environmental problems, they suggest that social science should not be cast aside in addressing the use of the term, and that "(…) attending to questions of power (of sectors, disciplines, forms of legitimate knowledge, stakeholders) is a crucial but often underplayed aspect of integration, and inadequately addressed by many actors in the nexus debates" (p. 169). Addressing the nexus from this broader perspective makes it a matter not just of modelling, but also of governance.

In a recent review article, Urbinatti et al. (2020) highlight the main narratives emerging from scientific papers that address the role of the nexus at the science-policy-society interface. They discuss the complexities and uncertainties associated with the nexus and introduce the term "nexus of humility" to encompass the dimensions of framing, vulnerability, distribution and learning. This resonates with Jasanoff's notion of "technologies of humility" (Jasanoff, 2007a), calling for scientists to recognise the limits to their knowledge, and for policymakers to bring ethical dimensions at the forefront of

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[1] https://iaste.info/

decision-making. The definition of complexity that this thesis builds upon is very much in line with these views. The nexus between social and environmental dimensions is complex in that it can be framed differently by different actors. Power relations, thus, have a part to play in determining whose framing becomes dominant, and how nexus assessments are instrumentalised. A humble approach to viewing this complexity is one that recognises inherent trade-offs, uncertainties and values. While this is no easy task, the work presented in this thesis is an attempt to operationalise this approach. This is also what the MAGIC project has set to achieve from its inception. In the next section, I describe MAGIC, its philosophy and its pre-analytical and analytical approaches.

1.1.4. MAGIC and Quantitative Storytelling[2]

The Horizon-2020 project MAGIC, short for Moving Towards Adaptive Governance in Complexity, aims at checking the quality of narratives underpinning EU sustainability policies, through mixed qualitative and quantitative methods. The project includes ten partners, each focusing on particular nexus dimensions, with researchers spanning the natural and social sciences. MAGIC addresses policy through a procedure called Quantitative Storytelling (QST), shown in Figure 2. QST was developed within the project as a common methodological ground for transdisciplinary nexus research. At the start of the cycle, narratives relevant to a given problem are identified. From those narratives, nexus problems to be explored are selected. This is where the quantitative analysis takes place. The information produced by the quantitative analysis is then interpreted, feeding back into the pool of general narratives on the topic.

There are two analytical tools, one qualitative and one quantitative, underpinning the QST cycle. The first is the narrative taxonomy used to map policy narratives. I will introduce this narrative taxonomy in Chapter 3. The second is MuSIASEM, short for Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism. The main principles of MuSIASEM will be discussed in Chapter 2, and MuSIASEM will also be applied in Chapter 5.

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[2] This section is partly adapted from a forthcoming paper with Maddalena Ripa, Violeta Cabello and Cristina Madrid, on lessons learnt when applying QST to the study of innovations

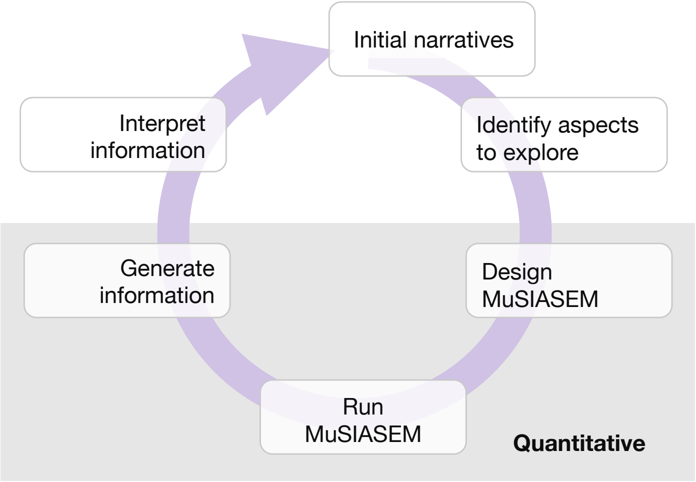

Figure 2. The cycle of Quantitative Storytelling (QST)

In addition to narrative analyses and integrated assessments, case studies developed within MAGIC may include engagement events, such as interviews and roundtable discussions, within different stages of the QST cycle. The inclusion of a wider peer community, through engagement, stems from MAGIC's grounding in Post-Normal Science (PNS). PNS is a type of science that distinguishes itself from the Baconian/Cartesian/Netwonian/Darwinian/Comtean (BCNDC) version of science[3]. It does so by moving science's objective away from one of prediction and control towards one of exploration, recognising the existence of uncertainties and value systems. Placing itself within PNS, QST aims to highlight trade-offs that are inherent to nexus relationships, contributing to a set of narratives that embraces complexity, rather than trying to reduce it. Looking back at Figure 1, this entails moving away from the model of "scientific advice". By complementing quantitative assessments with narrative analyses, QST steps outside of the dominant epistemic boxes, questioning the validity of the upper narratives defining each box. Given the highly collaborative nature of MAGIC, it is important to note that much of the work presented in this thesis was borne from discussions and collaborations with researchers both at UAB and at other institutions, and none of it can be considered outside of the wider scope of the project.

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[3] I found the term BCNDC science in Salthe's book "Development and Evolution: Complexity and Change in Biology" (Salthe, 1993). I am unsure as to whether he coined the term himself or whether it is also used by other authors.

1.2. Theoretical frameworks

1.2.1. Complexity: an overview

As part of his yearly lecture on networks presented at the Santa Fe Institute (SFI) Complex Systems Summer School, Cristopher Moore circularly defines complex systems science as “what complex system scientists do”[4]. This ironic take responds to the ambiguity of the terms “complexity” and “complex systems science”. This ambiguity is not a result of a lack of definitions. Rather, it stems from the co-existence of multiple ones. There are three reasons that lead to a plurality of framings and definitions of complexity. The first, and perhaps simplest reason, is a combination of the exponential popularity of the term and of the interdisciplinary settings in which it is being invoked. The second reason has to do with the existence of different types of definitions, i.e., whether we are talking about the “essence” of complex systems (following Aristotle), or of the content of the concept of complexity (following Kant) (Gorskij, 1970). Thirdly, the plurality of definitions of complexity may be a result of complexity itself.

The first issue raised, that people in different fields may define complexity under different terms and using different examples, is not particularly interesting for the purpose of understanding what complexity *is*. The second point, i.e., the distinction between definition as revealing the essence of a thing, and explaining the contents of the thing, is useful in ordering existing definitions of complexity. Revealing the essence of something can be thought of as defining what the system *is*, while explaining its contents can be thought of as defining what it does, how it does it, or how it came to be. The latter typology, also known as explicative definitions, is the most common in complex system science. Here, properties of complex systems are used to define them. In the Introduction to his book “Complexity and Postmodernism”, Paul Cilliers ascribes ten properties to complex systems: they are comprised of a large number of elements; elements interact dynamically (but interactions do not have to be physical); elements of the system influence and are influenced by others; interactions are non-linear; interactions are short-range; there are loops in the interactions; the systems are open; the systems operate under far-from-equilibrium conditions; there is historical path dependency; each element of the system is ignorant of

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[4] This follows Bridgman’s operational definition of science as “what scientists do” (Bridgman, 1955)

the behaviour of the system as a whole (Cilliers, 1998). Many of these kinds of definitions can be found in the literature on complexity, with some of these properties being inter-related, such that it would probably suffice to refer to a smaller set, as is often done by defining complex systems as ones where multiple elements interact dynamically to produce emergent behaviour, with no element having knowledge of the behaviour of the whole. This framing is useful to describe systems that are popular in complexity science, such as ant colonies or neural networks.

Stanley Salthe follows the former typology of definition, attempting to summarise the different ways in which complex systems have been defined in their essence, and not in their properties. He refers to two ways of defining complex systems – from a semiotic perspective, or from an ontological one (Salthe, 1993). Salthe's own ontological definition refers to complex situations, rather than complex systems: "a situation is complex when two or more systems occupy the same physical coordinates but do not regularly interact" (p.5). This is similar to Nicolis' definition of structural complexity, which focuses on the interactions between elements: structural complexity increases the more elements are interacting, the more they are connected to one another, and the higher the variance of the probability density function of the strengths of interactions among elements. A semiotic view, on the other hand, highlights the role played by the observer in defining the complexity of a given system. This can be, for example, in defining complexity through a measure of it (what are also known as operational definitions (Gorskij, 1970)). Operational definitions of complexity state that " (…) something is complex if it takes a long message to describe it and/or if it takes a long time for it to be made "or to make itself" (Salthe, 1993, p. 3). This is also known as Kolmogorov complexity. Common measures of complexity include information content, information capacity and logical depth. Rosen's metasystemic view of complexity is also included by Salthe under the class of semiotic definitions, although it is not operational. According to Rosen, a complex system is one that can be described in multiple, non-equivalent ways. Thus, the observer is not only relevant as the one observing and measuring the system, but also as a plural entity which may observe and measure the system differently depending on her own ontology, and as one which affects the system itself, while being affected by it. In this view of complexity, narratives become central, as they are the devices used by observers to (i) identify systems at a given scale and (ii) observe them. The relationship between Rosennian complexity and narratives will be discussed in Section 1.2.4.

Taking a perspective from biology, the philosopher of science Sandra Mitchell makes the distinction between constitutive complexity and dynamic complexity[5] (Mitchell, 2003). Constitutive complexity has to do with the architecture of complex systems, with the whole being formed by parts that are organized in a non-random way (i.e., Aristotle's formal cause). Dynamic complexity focuses on the processes that lead simple entities to becoming complex ones. It is particularly relevant to biology, for example in the processes transforming single-cell organisms to multicellular ones. The type of complexity that is most relevant to this thesis is the constitutive type, as I do not explore the evolutionary dynamics of social-ecological systems, nor do I ask how their complexity came to be, although these questions are undoubtably interesting and relevant to the study of the sustainability of societies (see, e.g., Tainter (1988)). Strand (2002) makes the distinction between thin and thick complexity. Thin complexity is a property of (mechanical) systems, while thick complexity arises from the relationship between system and observer. Interestingly, Strand also notes that complexity cannot be defined. This brings us to the last reason for a plurality of definitions of complexity. If we follow the type of complexity that is thick, relational or Rosennian, as one may refer to it, a single definition of a "complex system" cannot be provided because complexity lies exactly in the process of observing and defining the world. This type of complexity "(…) is an epistemological issue, not a property of the external world" (Allen et al., 2017, p.40). Rosen's definition of complexity allows for a plurality of definitions of complex system to exist.

Relational complexity is embedded in the observer-observed complex. This brings us to the notion of impredicativity. It is impossible to define simple time when representing complex systems. This is due to the fact that events at different scales are simultaneously affecting one another. A well-known example of this is the chicken-egg paradox. Impredicativity refers to these causal loops happening across scales. The concept of narrative, then, becomes important as it allows observers to eliminate impredicativity, identifying a chosen direction of causality. Impredicativity is different from unpredictability, as a system does not have to be complex, but simply evolving in time, to be unpredictable (although this may very well mean that the system is complex, depending once again on the chosen definition of complexity). To understand impredicativity, and Rosennian

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[5] Mitchell also refers to "evolved complexity", but elsewhere she calls this "evolved diversity", providing a different definition suggesting that this is not a "type" of complexity, but a consequence of dynamic complexity, i.e., the evolution of a diversity of organisms

complexity, it is useful to introduce Rosen's modelling relation (shown in Figure 3). *N* denotes the perception of a natural system and *F* a formal one built on that perception. The perception of a natural system requires a pre-analytical choice about what makes the system (the observer has to be at a given scale and has to identify something as "a system"), as well as a set of narratives allowing for the perception of causal relationships within the system. Formal models are then built based on this perception, with the aim of describing the natural system in a way that is adequate to a given purpose. These two systems are connected through the actions of encoding and decoding. Through encoding, a natural system is mapped onto a formal one (remembering that a plurality of encoding relationships is possible). Encoding is necessarily carried out by a finite set of proxy variables (Giampietro et al., 2006). There can never be complete (or perfect) knowledge, as this would require infinite variables. Through decoding, the validity of the formal system is checked against the perceived reality of the natural one. This relationship underpins the scientific process. The existence of a natural system requires a pre-analytical (normative) choice, where the observer decides what is relevant (*why* a certain thing should be studied) in the perception. Anything which is not considered relevant is framed as noise (Giampietro et al., 2006). Encoding, then, provides a formal identity to *what* is observed (the set of observables associated with the natural system). With decoding, the formal model is checked against the perceived reality (determining *how* events are connected).

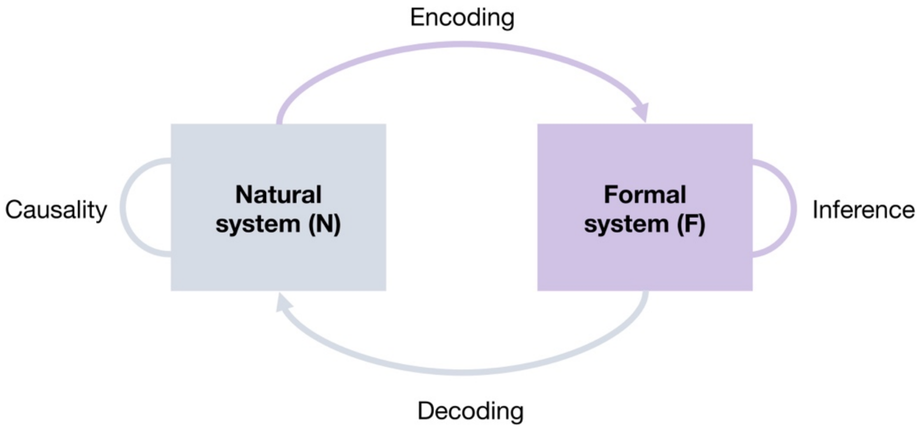

Figure 3. Rosen's modelling relation. Adapted from Rosen (2012)

Impredicative systems are open to material causation and closed to efficient causation (Giampietro, 2019). A social-ecological system, for example, is materially open as it requires flows of inputs from its environment and from other systems in order to survive (such as food or energy) (Prigogine and Nicolis, 1971). It is also closed to efficient causation, as it generates its own meaning and purpose. Building on this, throughout this thesis, complex systems will be described as being impredicative, rather than unpredictable. Rosen's impredicativity is fundamental to understand his conceptualization of anticipatory systems (Rosen and Kineman, 2005; Louie, 2010; Rosen, 2012; Poli, 2019). An anticipatory system is one "(…) containing a predictive model of itself and/or its environment, which allows the system to change state at an instant in accord with the model's predictions pertaining to a later instant" (Rosen, 2012, p. 313). The model that the system has of itself is the formal model *F* in the modelling relation. This notion of anticipation is significant, as it assumes not only that complex systems have a function, or purpose, but also that they are able to act based on something which has not happened yet. This places itself in radical contrast with the linear view of time which characterises BCNDC science. For more on the implications of anticipation for time, linearity and science, see Poli (2019). These concepts are related to the sustainability of social-ecological systems, and to their governance: social-ecological systems are complex, impredicative and anticipatory. Impredicativity is tied to the multi-scale nature of complex systems. This brings us to the theories related to the architecture of complexity, including holarchies and hierarchies. Focusing on the organisation of complexity across levels, the next section introduces the main principles of hierarchy theory.

1.2.2. Hierarchy Theory[6]

Hierarchy theory is the branch of complexity developed by Simon (1962; 1977), Allen and Starr (1982), Pattee (1973) and Salthe (1985), among others. While popular definitions of hierarchy evoke questions of centralized control, hierarchical systems do not necessarily reflect this type of control and can be defined in relation to observation. Lane (2006) clarifies this by making the distinction between control hierarchies and level hierarchies. Hierarchy theory is concerned with level hierarchies. In this view, as described

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[6] The content of this section is partially adapted from Section 2 of Diaconescu et al. (2021) and from Section 1 of Diaconescu et al. (2019)

by Whyte et al. (1969), "a system is hierarchical when alternative methods of description exist for the same system" (p. 468). Ahl and Allen (1996)'s definition of hierarchy theory, as "a theory of the observer's role in any formal study of complex systems" (p. 29), builds on this stance.

The role of the observer is inherently tied to the multi-level nature of the system. An observer is as any system interacting with another (Salthe, 1993). A person, a computer or a government can all be observers. Observers can be external or internal to the system, depending on the chosen system boundaries. E.g., I can study society while being a part of it, or I can study an ant colony as an external observer (although being external does not mean that I do not affect the formal representation of the system – it does not lead to objectivity). A minimum of three levels is necessary in describing complex systems: the focal level, i.e., the one where a certain phenomenon is being observed; the level above it, explaining the function of the observed behaviour; the level below it, explaining the structure. This means that hierarchical levels are relational, rather than fixed. According to Allen and Starr (1982), all systems are hierarchical, and not viewing one as such simply means that the observer is placed at the focal level of the system, not seeing the levels above and below. For example, a tree in a forest can be taken as the focal level of analysis. The behaviour of the forest patch of which the tree is a part constitutes its context and is necessary to understand the tree's function (or final cause, in Aristotelian terms). The tissues and parts making up the tree itself can be seen as the lower hierarchical level, defining its structure (or material cause). Taking a different perspective, the forest patch may be observed as the focal level, with its wider ecosystem being the functional layer, and individual trees being the structural one.

Elements at higher hierarchical levels do not necessarily contain lower-level ones in a physical sense. They may follow one or more of five rules (Wu, 2013): (i) they are the context of the lower-level elements; (ii) they constrain lower-level elements; (iii) they operate at a slower frequency; (iv) they have a higher bond strength and greater integrity; (v) they contain or are made of lower levels. For example, the EU political structures can be considered to be at a higher hierarchical level than the ones of the city of Barcelona which, in turn, are at a higher hierarchical level than the ones governing an individual household in the city. These higher-level structures do not physically contain the lower ones, but they provide the context for lower-level ones. Importantly, while higher levels may constrain or provide the context to lower ones, causation in hierarchies is not uniquely directed, since lower-level elements of the hierarchy also affect higher-level elements.

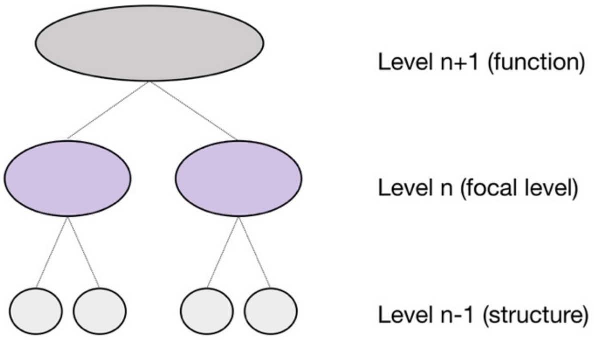

Figure 4. Three-level structure of hierarchy theory

This is also referred to as upward causation, while the whole affecting its parts is referred to as downward causation (Flack, 2017). The three-level structure of hierarchy theory, as shown in Figure 4, means that each element at the focal level is simultaneously part of something else, while being made of smaller parts (bearing in mind that this composition is not necessarily physical). This whole-part duality is conceptualized by Koestler through the term "holon"(Koestler, 1967). He then refers to the term "holarchies" when describing nested hierarchies of holons, similar to what is shown in Figure 4. Relational complexity is about the study of holons, since complex adaptive systems express function and structures across multiple levels and scales (Giampietro et al., 2006).

The hierarchical nature of complex systems is also central to Simon's work on the architecture of complexity (Simon, 1962; 1977). In discussing multi-level systems, he highlights the near-decomposability property of hierarchical levels, which can be analysed quasi-independently from each other. There is an advantage in the evolution of complex systems, as each level provides a stable intermediate component for the level above, exemplified through the famous watchmaker analogy. Operator hierarchy theory, developed by Jagers Op Akkerhuis (2010), makes the useful distinction between functional and structural closure across hierarchical levels. Structural closure refers to levels that are materially nested (closed to material causation), while functional closure refers to the situation where higher levels are related to lower ones through mutually dependent transformation processes, with lower-level processes being necessary for the process of the whole. An example of this type of closure, also known as relational closure in cybernetics (Heylighen, 1990), are autocatalytic sets of proteins (Kauffman, 1986). Holons are central to Rosennian complexity, which can be described, in different terms, as the study of holons, rather than the study of a material reality “out there”. In the next section, social metabolism is introduced, as a way to apply these concepts to the study of social-ecological systems.

1.2.3. Social metabolism[7]

Social metabolism is an application of hierarchy theory to the study of social-ecological systems, in combination with principles from theoretical ecology and energetics. In order to survive, living systems rely on interconnected chemical processes, metabolising inputs from their environments. Similarly, societies metabolise material inputs from their embedding ecosystems, through interconnected process that rely on one another. In both cases, the system is also connected to its environment through flows of outputs and waste. Lotka (1956) first made the distinction between these two metabolisms by using the terms endosomatic and exosomatic metabolism. Georgescu-Roegen, whose flow-fund theory MuSIASEM builds on, was also a strong supporter of the idea of exosomatic metabolism.
As the words suggest, endosomatic metabolism refers to the processes taking place inside the human body. Exosomatic metabolism refers to the processes taking place outside the human body – for example, the primary energy sources extracted from the environment and processed through exosomatic technologies. The use of the term “metabolism”, as applied to societies, is not a metaphor, but denotes metabolic processes taking place at a different hierarchical level than the one of living organisms, where the term is most often applied.

Through the lens of social metabolism, social-ecological systems are multi-scale, open, dissipative and far from equilibrium. They are also “becoming systems”, since they change their identity over time (Prigogine, 1980). For example, a university can be viewed as a social-ecological system encompassing structures, functions and environments. The identity of the institution may change over time, e.g., it may shift from being a catholic university to being a secular one. This may have effects on the way parts of its environments are managed, for example with the secular shift leading to more buildings being built,

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[7] Parts of this section are adapted from the same forthcoming paper with Violeta Cabello, Maddalena Ripa and Cristina Madrid mentioned in footnote 2

affecting the local fauna. Students of the institution may go through different changes due to other drivers, for example with the student body decreasing due to national lack of funds. The students, the institution and the environments, each affecting one another, are becoming at different timescales. The fact that social-ecological systems are becoming across multiple scales, then, requires the simultaneous adoption of multiple scales of analysis. The way this is operationalized in the MAGIC project, and throughout this thesis, is through the development and application of MuSIASEM. Conceptually, MuSIASEM relies on three theoretical branches: non-equilibrium thermodynamics, complex systems theory and bioeconomics (Giampietro et al., 2009). While I have given space to explain the grounding in complex systems theory, providing further theoretical grounding in the fields of non-equilibrium thermodynamics and bioeconomics is outside of the scope of this thesis. Instead, I try to explain in simple terms the principles of MuSIASEM.

MuSIASEM produces system perspectives of sustainability issues, by organising data across four axes. The first two axes pertain to the scale of the system. Following hierarchy theory, MuSIASEM disaggregates the behaviour of a system as a whole (e.g., a region), into the behaviour of its functional parts (e.g., its economic sectors), focusing on relations within and across levels. A multi-scale perspective is achieved by simultaneously describing the behaviour of the part and that of the whole (e.g., the amount of electricity consumed by each economic sector, and the total electricity consumed by a region). Scale is also included in MuSIASEM in terms of spatial scales. Similar to how hierarchical levels are nested (the electricity consumed by all economic sectors is equal to the electricity consumed by the whole system), so are spatial scales (the electricity consumed by all regions is equal to the electricity consumed by the country). Moving past scales, the other two axes of MuSIASEM are binary and pertain to the type of variable that is being quantified. MuSIASEM makes the distinction between those variables that are related to the biosphere, and those that are related to the technosphere. This is the core of nexus assessments, where environmental variables (e.g., GHG emissions and use of freshwater) are coupled with socio-economic ones (e.g., hours of labour and energy consumption). Finally, it makes the distinction between system elements that process, metabolize or transform material flows and system elements that are produced, consumed and transformed. Building on the field of bioeconomics, the former are referred to as flows, the latter as funds (Georgescu-Roegen, 1971). This leads to four categories of variables (technosphere funds and flows, biosphere funds and flows), each specified at a given hierarchical level and spatial scale. These variables are connected through a tool called the *metabolic processor*, which will be introduced in Chapter 2, and applied in Chapters 2 and 5.

Without delving deep into each category, what characterizes MuSIASEM is a focus on the relations among variables. MuSIASEM does not aim to generate *correct* quantitative assessments, but *robust* ones. The robustness of a number lies in the coherence between that number and others. The more different variables (e.g., biophysical, economic, at different scales) are linked to one another, the more robust they are, since relations constrain numbers within a space which guarantees their coherence to one another (what is also known as the "Sudoku effect" of MuSIASEM (Giampietro and Bukkens, 2015)). Coherence also comes into play at a different scale, not only in the relations among variables, but also in the relations between numbers and narratives. There are three types of coherence checks: internal coherence with the same dimension across levels (e.g., the coherence of energy quantities across scales); external coherence across dimensions (e.g., the coherence of energy with monetary variables); semantic coherence between the model, the selected narrative and the relevance of its concern. The latter is central to policy. The next section focuses on the implications of Rosennian complexity for policymaking.

1.2.4. Complexity, narratives and policy

The fact that a complex system may be viewed and described in non-equivalent and non-reducible ways by different observers has implications for the science-policy interface. Reality is ordered by entities through narratives, tying information from different scales into a coherent storyline. This includes policies, where narratives are used to order events and to give priority to certain aspects over others.

Existing theories conceptualise the role that narratives and storylines play in policymaking. Two notable ones are Narrative Policy Analysis (NPA), developed in the 1990's, and more recently the Narrative Policy Framework (NPF), developed in the 2010s. NPA was presented by Roe in 1994 in the book "Narrative Policy Analysis: Theory and Practice", where they applied contemporary literary theory to public policy issues. It builds on the distinction between policy scenarios, policy arguments, alternative narratives and policy metanarratives. Policy scenarios are those narratives having a beginning, a middle and an end, while policy narratives "underwrite the policy assumptions of policymaking" (Roe, 1994, p. 155). Alternative narratives, on the other hand, are those that are not aligned with dominant policy narratives (Jones and McBeth, 2010). In an act of synthesis, policy metanarratives are generated by comparing dominant and alternative ones, adding more dimensions to the initial narrative. The Narrative Policy Framework is a systemic approach to Narrative Policy Analysis. It defines two levels of analysis: micro and meso. At the micro level, NPF checks how policy narratives affect individuals' perception of issues; at the meso level, it checks how policy narratives affect policy outcomes. For more on both NPA and NPF, and for an overview of the role of narratives in public policy, see Jones and McBeth (2010).

This underlying process of NPA process is similar to the QST cycle presented in Section 1.1.4., although the goal in MAGIC is not so much to produce policy metanarratives, as it is to check whether existing policy narratives are adequate at addressing sustainability concerns. The distinction between dominant and alternative narratives is also discussed by Longhurst and Chilvers (2019). Dominant narratives are those generated within centres of power. These centres could be government institutions, academic ones, lobbies, etc. There can be contrasting dominant narratives at different spatial scales, e.g., EU narratives versus those of a local government. Alternative narratives are decentralized ones, generated outside of these centres of power. What makes a "centre of power" is also relative. The results of the MAGIC project, for example, are generated within an academic setting. These narratives could be considered dominant with respect to decentralized settings, or alternative with respect to official EU narratives.· On this, it is important to note that academia is not a uniform group, as it is also affected by different power distributions within it.

In this thesis, I introduce a narrative taxonomy which is orthogonal and complementary to existing theories. The taxonomy is aimed at mapping the narratives present in policy documents across hierarchical levels, identifying three types of narratives tied to policy measures: justification, normative and explanation narratives. Normative narratives answer the question: What should be done? Justification narratives answer the question: Why should it be done? Explanation narratives, finally, answer the question: How should it be done? These three types of narratives link to the questions of impredicativity and causality which were introduced Section 1.2.1. Any narrative eliminates information that is irrelevant to it in order to guide possible courses of actions. Justification narratives, specifically, frame (i) which issues are relevant and (ii) which actions are currently lacking in order to address them. An example of a justification narrative is "GHG emissions need to be reduced to fight climate change", where climate change is the relevant issue, and the lack of GHG emission reduction is the concern. Normative narratives focus on the causal relational between the concern, and the action to be taken. For example, “To reduce GHG emissions (concern), we need to decarbonise the economy by 2050 (action)”. Explanation narratives, then, focus on the causal relation between the action to be taken, and the practical mechanisms guiding that action. In this example, “To decarbonise the economy by 2050 (action), we must install more solar panels (mechanism)”. Importantly, the distinction between concerns, actions and mechanisms is relational, similar to the distinction between function, focal level and structure introduced in Section 1.2.2., where levels are observer dependent. In Chapter 3, I will apply this narrative taxonomy to the case study of electric vehicles in the EU.

If we accept that different entities will inevitably use different narratives to make sense of complex realities, the question of how to integrate this plurality of views in our models of the world becomes urgent. Mitchell (2003) uses the term “integrative pluralism” to defend the integration of a plurality of non-equivalent views. This resonates with the concept of situated knowledges in feminist studies (Haraway, 1988), of civic epistemologies in science and technology studies (Miller, 2008; Jasanoff, 2007b) and of epistemologies of the South (Santos, 2015). It is also in line with methodologies aimed at embracing pluralism, such as Soft System Methodology in systems engineering (Checkland, 1989), multicriteria assessments and the “opening up” of governance in ecological economics and sustainability science (Munda, 2004; Stirling, 2008). Pluralism is also embraced by post-normal science, as a means to avoid hegemonisation (Funtowicz and Ravetz, 1994). These pluralistic approaches recognise that phenomena have no single causation history, partially as a consequence of the multi-level interactions that take place in complex systems. Ultimately, they call for a plurality of explanations to be embraced. This does not mean that there are multiple worlds, but that there are multiple, valid ways of parsing the world (Mitchell, 2003). In this way, pluralistic approaches distance themselves from epistemological anarchism (Feyerabend, 1993). In simple terms, they do not mean that “anything goes” (Stirling, 2010). In embracing the different knowledges we may have of the world, pluralism is tied to uncertainty. Knight (1921) makes the distinction between four types of uncertainties: perception uncertainty, anticipation uncertainty, effect uncertainty and implementation uncertainty. All of these types are built within the architecture of Rosennian complexity, as they are the result of the necessarily limited knowledge that a formal system represents (perceptions are necessarily different from representations). Complete knowledge of complex reality is an impossibility, as completeness would require that a single view of reality can be taken. This does not mean that some uncertainties cannot be reduced, but it suggests that acknowledging complexity requires us to be aware of uncertainty and to find ways of working with it, rather than trying to eliminate it. The way uncertainty is mobilised in the spheres of governance and decision-making, then, is tied to the questions of choice and power relations. Power relations are not addressed directly in this thesis. However, their recognition is necessary when discussing policy measures, as uncertainty attached to given measures may be mobilised either in favour or against it, depending on the dominant narrative. This, in turn, is related to the role of choice in constructing narratives. Lissack (2019) argues that selection of narratives to parse the complexity of the world relies on agency and choice. He writes: "We choose the aspects of the world we consciously pay attention to, we choose the shortcuts we use in paying that attention and, in making those choices, we play an important role in constructing both the context for our actions and the understandings we use to explain them." (p. 234). This "we" can be applied to scientists and to decision-makers alike, although agency may be restricted by a number of factors.

To add a layer of complexity, often we may not have knowledge of the choices and assumptions made in building narratives. This can be through what Polanyi described as tacit knowledge, whereby we are not aware of knowledge that we have of something (Polanyi, 1961). Unawareness of knowledge, however, can also be tied to where knowledge resides: an institution may have some knowledge, but may withhold it from the public. A third type of knowledge is addressed by Rayner (2012) as "uncomfortable knowledge". This is knowledge which is in tension which the self-consistent versions of the world created by entities (where entities can be people, institutions, etc.). This may be, for example, knowledge held by a company whose brand revolves around sustainability, that their products are unsustainable. At the institutional level, uncomfortable knowledge manifests itself as that which goes against the principles that underpin the very existence of the institution, or its modus operandi – e.g., degrowth narratives are uncomfortable in a for-growth European Commission. Uncomfortable knowledge has become a popular phrase in the MAGIC project when referring to the type of results that we are producing.

This brings us to the term "adaptive governance", which is part of the MAGIC acronym, and to the role played by science in this new form of governance. The World Bank defines governance as "the manner in which power is exercised in the management of a country's economic and social resources for development" (World Bank, 1991, p.1). Governance is not just a matter of political structures, legislation and institutional processes, but also one of informal arrangements, power relations and values. "Adaptive", on the other hand, refers to a system of governance which can anticipate changes and adapt accordingly. If resilience can be thought of as the ability of a system to maintain its function under perturbations, adaptivity refers to the capacity of a system not only to adapt its structures in order to meet its function, but also to change the functions themselves, in order to survive (Holling, 2001). Thus, adaptivity requires self-awareness and flexibility. Investigating the relationship between scientific models, reality and power (in the sense of policies and decisions), relational complexity can contribute to this self-awareness.

In this view, acknowledging complexity does not mean producing a different kind of knowledge to inform decision-making (although this is part of the process): it does not mean 'speaking a different kind of truth'. Instead, Rosennian complexity shifts the relationship between science and policy, analysing it and bringing the scientific process inside the messiness of governance. This is why it makes sense to talk of adaptive governance *in* complexity, rather than of adaptive governance *of* complexity. In this thesis, I do not provide answers as to how an institutional shift to adaptive governance in complexity should be managed. Instead, I focus on the role played by science in this science-policy relationship, providing a set of case studies which can help in understanding the relationship in the realm of energy policy.

1.3. Research questions

The content of this thesis is motivated by two underlying questions at different levels, each feeding into the other. The first question is of methodological nature. I ask:

"How can different perceptions of social-ecological systems be modelled across levels and dimensions, building on the principles of hierarchy theory and social metabolism?" (Q1)

The second question is reflexive and builds in two steps. I ask:

"What does the current relationship between scientific knowledge and sustainability policy look like, when inspected through the lens of complexity?" (Q2A)
&
"What is the role of alternative narratives and models built in complexity in shifting the current science-policy relation?" (Q2B)

Each chapter to follow will contribute to an understanding of these questions, while relying on its own, case-specific set of research questions. It is in the development of case-study research questions that I enter the realm of energy policy and dig deeper into specific aspects of sustainability. Chapter 2 contributes to the first question. I take Catalonia's electricity sector as my case study, and model it following the principles of hierarchy theory and social metabolism. Elements of the electricity sector are mapped into functional and structural components, building on Koestler's notion of holons. I then discuss the potential utility of this model for policymaking, tapping into the second research question. Chapter 3 steps away from model-making, taking a reflexive stance. Here, Zora Kovacic and I ask how energy security is conceptualised in academia. From the plurality of definitions, we argue that the ambiguity of the term is functional to policymaking, and a consequence of complexity. These considerations build to an understanding of the science-policy relationship through the lens of complexity, contributing to question 2A.

Chapter 4 continues along this line, this time inspecting the relationship between existing knowledge about electric vehicles, and their policy narratives found in EU documents. I ask: Why does the EU want to implement electric vehicles? Is current science aligned with these justifications, and what is the relationship between science and policy narratives? Chapter 5, then, expand the methodology presented in Chapter 2, both in terms of scale and in terms of the modelled system. I describe the full energy systems (electricity, heat and fuels) of Spain, Sweden and the EU across hierarchical levels, including externalized energy processes that take place outside the national and supra-national boundaries (Question 1). I then use these models to discuss two topics that are central to EU energy policy: externalisation and decarbonisation. In the Conclusions, I return to the underlying research questions. I summarize my main methodological findings and place the results of each case study in the framing of Question 2B, asking how the kind of uncomfortable knowledge generated can be used to shift the science-policy relationship.

Chapter 2

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

This chapter presents work published in Di Felice et al. (2019), with minor edits. I introduce a multi-level model of energy systems, including nexus patterns at each hierarchical level. The model recognises the role played by both pre-analytical and analytical choices in shaping energy assessments. It is built to accommodate different variables and relations across scales and is not intended to produce narratives that are ultimately true. Rather, it is built produce narratives which are consistent across levels of analysis. Although the focus is on energy, I tie it with other nexus elements, including water, land, emissions and labour. This is in contrast with the current model of scientific advice informing EU policy, where large market-oriented energy models dominate as the tool to inform decision-making. I propose an alternative defined by three characteristics: (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 *metabolic processor*. To illustrate the model, it is applied to Catalonia's energy sector, linking production and consumption patterns. This methodological work is the foundation for the case studies which will be presented in Chapter 5.

2.1. 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, mono-disciplinary 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 even more clearly understood that circumscribed mono-disciplinary or single-sector approaches are not enough" (p. 2). 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 (EC, 2016b), 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 through nexus assessments, EU policy is informed by a linear approach. Different models specialising in the accounting of different elements provide the input for other models specialising in other elements, and so on. The EU's most recent modelling exercise informing policymakers on energy, transport and climate issues, the 2016 Reference Scenario, 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" (EC, 2016a, 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[8].

While concatenating inputs and outputs of different models provides some form of nexus analysis, it does so in a way that is grounded in Cartesian science, breaking up system components and then reassembling them. In addition, the inner workings of the models used to inform EU policies are not open for deliberation, as the modelling codes are not available to the public. Taking a stance grounded in relational complexity, we argue that moves towards interdisciplinarity in energy studies should recognise that the same energy issue can be viewed differently depending on chosen pre-analytical and analytical choices. Thus, models informing decision-making should allow for deliberation both in the choice of what to observe and in the choice of how to observe it, rather than providing a rigid set of outputs building on uncontested assumptions. These hidden assumptions could become contested if made explicit. Instead, market-oriented energy models "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).

As an alternative, our model aims to assess nexus elements simultaneously within a coherent framework which integrates information at different scales. In this way, we avoid contributing to "nexus imaginaries" (Cairns and Krzywoszynska, 2016), where nexus assessments are used to push for technocratic, win-win policy solutions. All the opposite, a transparent framing of assumptions across hierarchical levels may generate uncomfortable knowledge for policymakers, showing that win-win solutions for all are rarely possible.

The aim of this Chapter is methodological: building on the foundations of MuSIASEM, I propose a method to integrate quantitative information on nexus elements across

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[8] For an overview of the characteristics of each model, see EC (2016a)

hierarchical levels of the energy system. What characterises 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 Koestler's notion of holons (Koestler, 1967), and between funds and flows, following Gerogescu-Roegen's flow-fund model (Georgescu-Roegen, 1971). We use the example of Catalonia's energy sector to introduce and explain the model. Section 2.2. provides background on existing energy-nexus assessments and on MuSIASEM. Section 2.3. outlines the rationale of the model, building the methodology from the bottom-up. Results and discussion follow, focusing on the policy relevance of the methodology.

2.2. Energy-nexus assessments

Existing modelling tools integrating energy assessments with other nexus elements either take a lifecycle approach or a system perspective (Keairns et al., 2016). The latter include the Climate Land-Use Energy and Water Strategy (CLEWS) modelling framework, the Stockholm Resilience Centre'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 Societal 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).

The foundation of energy assessments with MuSIASEM is to acknowledge the complexity of the concept of energy, which is semantic in its nature. It 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 as the amount of oil and coal in the earth's lithosphere. Energy carriers (ECs) are the flows used for transformations under human control, for example electricity, heat and fuels. End uses reflect the final causes of the energy carriers (e.g., consumed in the household sector for heating). In addition to the conceptualisation of different energy flows describing energy transformations in society, MuSIASEM categorizes relevant elements of energy systems into funds, flows and stocks, following Georgescu-Roegen's flow-fund model (Georgescu-Roegen, 1970). 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 *metabolic 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 (Louie, 2010). 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 Parra et al. (2018; 2020) to describe and anticipate the metabolism of oil extraction in Ecuador and by Giampietro (2019) to anticipate changes in the social structure in relation to agriculture. For more recent applications, see also (Cadillo-Benalcazar et al., 2020) and Ripa et al.

(2021). While their framing as a tool for nexus analysis is new in MuSIASEM, 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 metabolic processor is the "resource processing system" by Grenon (1978) as a tool for the WELMM method, which has not been applied as a tool for nexus assessments in recent years.

2.3. Methods

2.3.1. 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 described in notional terms as a node in a network metabolising inputs from the technosphere and the biosphere and producing outputs, both useful (to society) and released to the environment (e.g., emissions). In energy assessments, the useful outputs are different types of energy carriers consumed by society. At a lower hierarchical level, structural processors can be described 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. Functional processors, as we will see throughout this case study, are aggregations of structural ones.

Figure 5 shows examples of a structural and a functional processor which appear in this Chapter: the structural processor of a nuclear pressurised water reactor (PWR) and the functional processor of baseload electricity generation. There is no 1:1 mapping between 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 technosphere inputs and outputs to biosphere ones. Technosphere inputs are elements that are consumed or produced (flows) and maintained (funds) by society, therefore under human control.

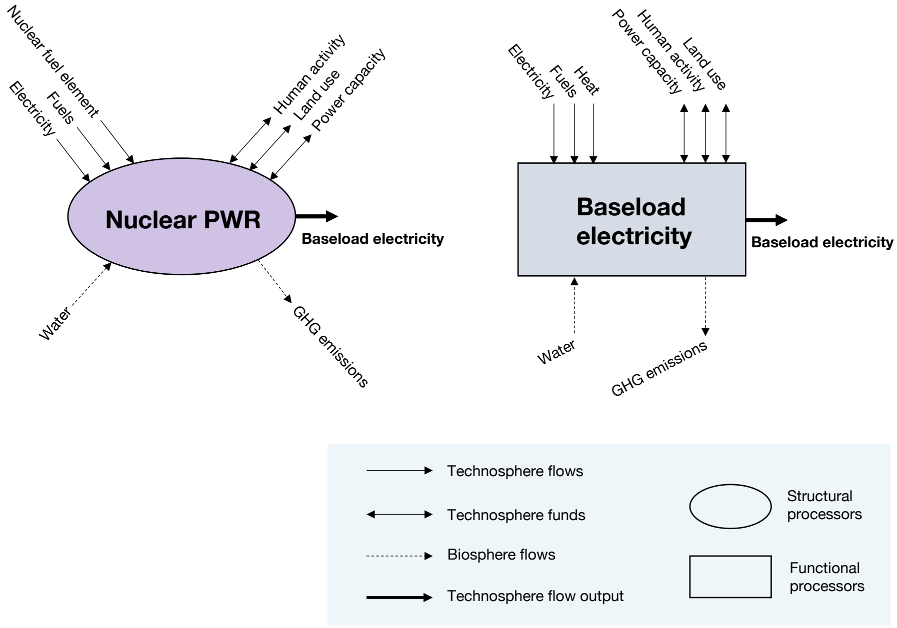

Figure 5. Example of a structural and a functional processor: Nuclear PWR and Baseload Electricity Generation.

They are represented on the upper half of the processor: flow elements on the left and fund elements on the right. Biosphere flows are either produced or received by processes in the biosphere (outside of human control), requiring a supply or sink capacity.They are represented on the lower half of the processor: flows inputs on the left (requiring a supply capacity) and flow outputs on the right (requiring a sink capacity). Both of these flows are tied to biosphere funds (not shown in the processor). Thus, each processor is associated with five sets of elements:

1. Technosphere flow inputs, for example the electricity from the grid consumed in a nuclear plant.
2. Technosphere fund inputs, such as the land on which the power plant is built.
3. Technosphere flow outputs for societal consumption, in this example a flow of baseload electricity, reflecting the final cause of the metabolic processor.
4. Biosphere flow inputs, such as freshwater abstracted for cooling.
5. Biosphere flow outputs, e.g., GHG emissions.

Flows are either produced by funds or extracted from stocks. 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 different processes. This leads to technosphere constraints. For example, the amount of labour or land that a process can use depends on how much is being used by others. Biosphere constraints to the behaviour of the metabolic pattern of societies also exist, 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.

2.3.2. Relations between processors across hierarchical levels

In this case study, hierarchies are intended as multi-level organisations of functions and structures, as described in Section 1.2.2. Figure 6 applies this to the energy system, showing an example of its multi-level composition. 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 Figure 6, only one hierarchical pathway has been expanded, from uranium and coal, to nuclear and coal plants, to the generation of baseload electricity needed in society (shown in bold).

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”.

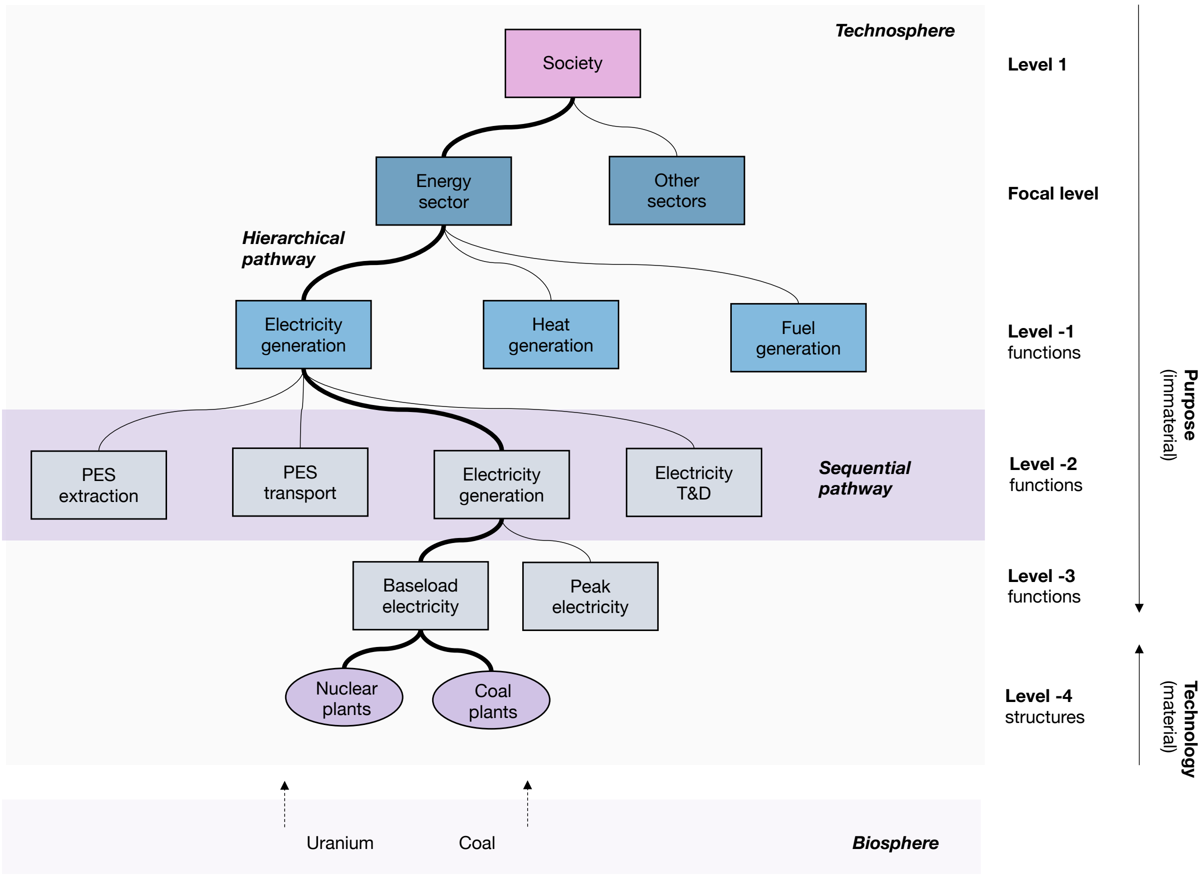

Figure 6. Hierarchy of structures and functions for the case study of Catalonia.

In this organisation, there is no 1:1 mapping between structures and functions: hydropower can be used to provide baseload or peak electricity depending on the context, and the "baseload electricity" functional element can be an aggregation of a different mix of processes, also depending on the context (for example, different countries have different mixes). Data taken at the structural level are aggregated and combined to describe the behaviour of the energy system at the functional level, and at the whole. The relations among different hierarchical levels follow simple rules of aggregation. Processors can be expressed intensively or extensively. Nexus inputs and outputs of intensive processors are all scaled by the main functional output (e.g., labour required for a nuclear plant expressed in terms of hours per MJ of electricity). Extensive processors only include extensive variables. Aggregating extensive processors simply implies summing lower-level elements. For example, the electricity consumed by the energy sector is the sum of the electricity consumed by each of its sub-sectors. Intensive processors are aggregated by considering the relative weight of each process with respect to the whole. In general, structural processors are described intensively, as data is not context-specific, while functional processors can be described both intensively and extensively, depending on the purpose of the analysis (intensive descriptions are required to build scenarios). 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, focusing instead 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. More details on the data and case study are included in the next section.

2.4. Data and case study

2.4.1. Data sources

To describe Catalonia's energy sector, data at different scales are collected. We refer to top-down data as data from 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, with full details included in the Appendix A1 (Table 12). In addition, for transparency and reproducibility, all data related to the case study, including calculations across different hierarchical levels, are freely available through Zenodo (Di Felice et al., 2019b). 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. On the consumption side, data on the consumption of energy carriers per sector are also obtained through ICAEN. The split between baseload, peak and intermittent electricity in sectoral consumption, however, is uncommon, and not available through statistical bodies. To obtain this, Spanish-level data from a 1998 report by the Red Eléctrica de España are used (Red Eléctrica de Espana, 1998). The report is old for the year in question, so the data on functional consumption of electricity can be considered to give a very general approximation of how different sectors consume electricity. Even if dated, most of these trends are expected to persist – e.g., a higher consumption of baseload electricity in the industrial sector. The report allows distinguishing between baseload and peak consumption curves in different sectors. For the consumption of intermittent electricity, we assume that the household and services sector consume the highest amount of intermittent electricity (10% of their total electricity consumption), followed by manufacturing (5% of its electricity consumption), followed by the other sectors (3% of their electricity consumption).

2.4.2. 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 rows of the Table extraction data of PES, as well as net imports, are provided. Following the MuSIASEM distinction between PES and ECs, the subsequent rows shows refinery process outputs and production of electricity, with their respective net imports. Data on uranium imports are not provided by ICAEN and have been derived by assuming that 0.73 kg of uranium are needed for each TJ produced in a nuclear PWR (Dones et al., 2007). Negative values in the production of energy carriers refer to products that are consumed in the intermediate refinery process, where the total consumption is higher than the refinery outputs, since only net outputs are available through ICAEN. Similarly, only net imports are available, leading to negative imports-exports balances.

Catalonia produces most of its electricity, while importing almost all of its crude oil and natural gas supply. For fuels, there is a high production of gasolines and gas-oils and imports of naphtha, fuel-oils and biofuels. This pattern is similar to that of other EU countries which are poor in natural resources and have a large amount of power plants as well as complex refining capacity, therefore importing PES to produce ECs. An overview of Catalonia's electricity sector is shown in Table 2. Each type of power plant is associated with its installed capacity, gross electricity generation and capacity utilisation factor (CUF), 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 (year 2012)

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	tU	0	63
Energy carrier	Refinery gases	ktoe	0	0
Energy carrier	Liquid petroleum gas	ktoe	364	260
Energy carrier	Naphtha	ktoe	-27	2157
Energy carrier	Gasolines	ktoe	1362	-495
Energy carrier	Kerosene	ktoe	871	244
Energy carrier	Gasoil	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

Table 2. Characterisation of Catalonia's electricity sector (year 2012)

Structural element	# of plants	Installed capacity (MW)	Electricity (GWh)	CUF (%)
Natural gas combined cycle (CC)	9	4112	8342	23
Nuclear PWR	3	3147	23996	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
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 treatment on farms	9	3	18	65
Total	564	12371	46040	

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.

2.5. Results & Discussion

2.5.1. Results across scales

The model is built by aggregating lower-level structural elements into a higher-level functional description. Mirroring Figure 6, Figure 7 shows the hierarchy of functions and structures considered in this case study. It has less levels, since we do not consider the full sequential pathways of the energy sector, thus moving directly from the focal level to the compartments of electricity, heat and fuel generation. We will refer back to Figure 7 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. The first step in the analysis is to build structural processors for different energy technologies fulfilling the role of electricity, fuel and 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 offshore 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.

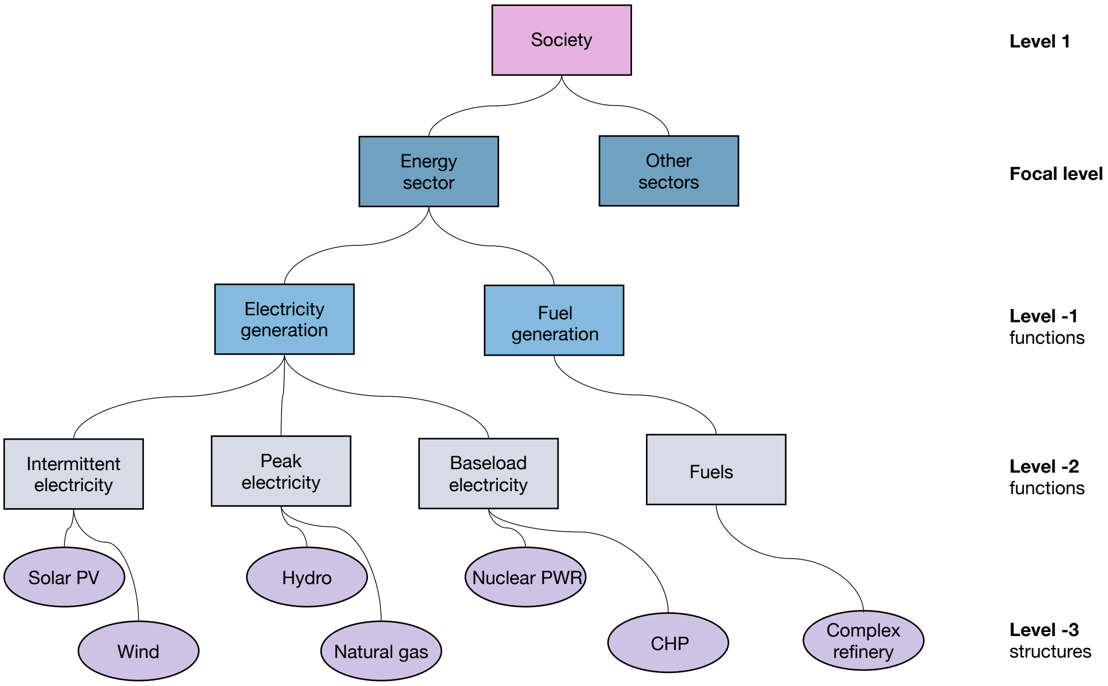

Figure 7. Functional aggregation of electricity production processors

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 are collected directly for the specific instance). In this Chapter, we refer to heat as 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, as heating fuels are produced by the refinery which is grouped under "fuel generation", and process heat is produced by CHP plants which are grouped under "baseload electricity generation". Focus hereon is given to electricity generation. 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. For water, 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. It describes the labour of operation & maintenance (O&M), and management overhead, accounted for in hours (hrs). 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 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. All of these choices and 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 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, and the structures are allocated to a chosen functional compartment. The refinery is allocated to fuel generation, and CHP to baseload electricity generation. This means that the functional processors for baseload electricity and for fuel generation have multiple EC outputs. There are limits to this kind of simplification, but by avoiding allocation methods, the inherent entanglement of patterns is explicitly addressed. Tables collecting the inputs and outputs of each structural processor, as well as their data sources are included in the Appendix (A1). Then, a functional grouping of structural processors is performed, aggregating them based on the functionality of their outputs, and moving up the hierarchy (Figure 8).

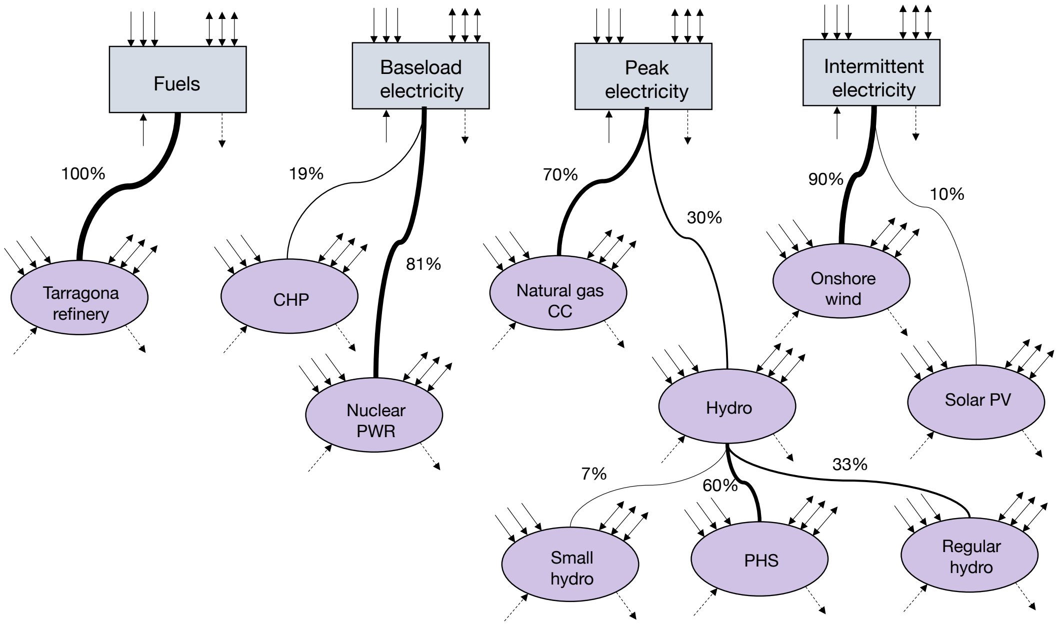

Figure 8. Structural to functional aggregation

For electricity, three functions are identified: baseload electricity, peak electricity and 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 (Lund and Mathiesen, 2009; Mason et al., 2010; Jacobson and Delucchi, 2011). While physically all electricity is the same, being a flow of electric charge (without considering the distinction between alternating and direct currents, outside of the scope of this discussion), its usefulness for society depends on how, when and where it is generated and how, when and where it is used.

Table 3. Comparison of intensive processors for baseload, peak and intermittent electricity (Level -3)

Type of input/output	Label	Unit	Baseload	Peak	Intermittent
Technosphere flow input	Electricity	MWh/GWh	42	23	20
Technosphere flow input	Fuels	GJ/GWh	216	0	0
Biosphere flow input	Water	m^3/GWh	161	474	0
Technosphere fund input	Human activity (HA)	hrs/GWh	111	57	151
Technosphere fund input	Power capacity (PC)	kW/GWh	140	544	504
Technosphere fund input	Land use (LU)	ha/GWh	0	0	11
Biosphere flow output	GHG emissions	t CO_2 eq./GWh	69	321	0

Table 4. Comparison of extensive processors for baseload, peak and intermittent electricity (Level -3)

Type of input/output	Label	Unit	Baseload	Peak	Intermittent
Technosphere flow input	Electricity	GWh	1260	271	6
Technosphere flow input	Fuels	TJ	6410	0	0
Biosphere flow input	Water	km^3	4790	5690	0
Technosphere fund input	Human activity (HA)	10^3 hrs	3290	686	451
Technosphere fund input	Power capacity (PC)	MW	4150	6530	1500
Technosphere fund input	Land use (LU)	ha	181	237	33100
Biosphere flow output	GHG emissions	t CO_2 eq.	2060	3850	0

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 3 shows how, for the same GWh of baseload, peak and intermittent power produced in Catalonia, a different pattern of flows and funds is needed[9].

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 151h 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 (and when strengthened through a sensitivity analysis). 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. In Table 4, inputs and outputs for functional electricity generation groups are included in extensive terms. This shows how, for example, intermittent electricity consumes more human activity per GWh produced than the other two types, but in extensive terms they are the sector which employs less human activity. 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.

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[9] This only includes "electricity generation" and a full comparison would have to include further steps in the energy chain (the full sequential pathway, e.g., extraction of materials needed for solar PV)

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 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 5 shows the inputs and outputs of the energy sector. The data in this case are extensive rather than intensive, therefore they are obtained by summing the extensive data of the three functional processors below it. The internal flow outputs, finally, can be allocated to different sectors of society (Table 6). Here, the split between baseload, intermittent and peak electricity is maintained, and the consumption of heat and fuels (in TJ) is also shown. As mentioned in Section 2.4.1, data on the split between baseload, peak and intermittent electricity, on the consumption side, is based on benchmarks and approximations. Maintaining this functional split in consumption patterns, even if inexact, is particularly useful in discussing policy pathways, as I address in the next section.

Table 5. Energy sector processor (Focal level)

Type of input/output	Label	Unit	Value
Technosphere flow input	Electricity	GWh	2.02E+03
Technosphere flow input	Fuels	TJ	8.27E+03
Biosphere flow input	Water	km^3	1.79E+04
Technosphere fund input	Human activity (HA)	103 hrs	6.28E+03
Technosphere fund input	Power capacity (PC)	MW	1.22E+04
Technosphere fund input	Land use (LU)	ha	3.39E+04
Biosphere flow output	GHG emissions	t CO_2 eq.	2.33E+06
Technosphere flow output	Electricity	GWh	4.67E+04
Technosphere flow output	Fuels	TJ	3.06E+05
Technosphere flow output	Heat	TJ	1.37E+05

Table 6. Consumption of energy carriers by economic sector (Level 1)

Sector	Baseload electricity (GWh)	Peak electricity (GWh)	Intermittent electricity (GWh)	Fuels (TJ)	Heat (TJ)
Energy sector (ES)	1760	100	100	8010	57800
Agriculture & Fishing (AF)	370	20	10	12390	5320
Manufacturing & Construction (MC)	14880	1160	500	9640	85080
Services & Government (SG)	7360	5880	1470	9300	13940
Households (HH)	5330	4260	1070	10430	41620
Transport (TR)	900	70	30	2277720	0

2.5.2. Policy relevance

The strength and novelty of this energy-nexus model lie in its ability to accommodate different pre-analytical and analytical framings. The hierarchical mapping moving from primary energy sources, to the technologies harnessing them, to their function in society may help in guiding the construction of energy-nexus narratives, providing a systemic picture of how different parts of the energy system connect to another. Moreover, 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 6 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. 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 6 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. This particular solution will be addressed in Chapter 4. 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 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, shifting the dominant narrative of a techno-optimist energy transition and giving space to alternative ones, such as the notion that consumption patterns may also need to be adjusted throughout a sustainable energy transition.

2.6. Conclusions

In discussing ecosystem models, Iwasa et al. (1987) suggest that, in order to simplify complex systems, attention should be turned to "techniques for choosing appropriate levels of aggregation" (p.288) . This observation resonates with the notions of multi-scalarity and complexity that are central to this thesis. The characteristics of complex systems can only be observed across different scales. The quality of a representation based on quantitative assessments across scales depends on the representation's ability to integrate non-reducible observations. This chapter has presented a simple hierarchical model quantitatively mapping nexus patterns associated with energy systems across levels. The case of Catalonia served as an example to highlight how populating the model with numbers may be useful in guiding policy discussions. The model 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. The strength of the model lies across two domains. The first is in the domain of energetics, by introducing the metabolic processor and describing functional elements of the energy system through nexus patterns. Secondly, the model can accommodate different pre-analytical and analytical choices. As such, it aims to contribute to a shift in science-policy relations, moving away from a paradigm of science speaking truth to power, and towards the co-production of knowledge among scientists, policymakers and other stakeholders.

Chapter 3

Complexity, uncertainty and ambiguity: Implications for European Union energy governance

Energy security, one of the pillars of the EU energy union, is an ambiguous term. This chapter presents work which has been published in Kovacic and Di Felice (2019), analysing the use of energy security in scientific publications and in EU policy. On the academic side, there has been growing interest in defining, conceptualising and measuring energy security, often through indicators. Energy policy in the European Union, on the other hand, is not concerned with energy security's ambiguous conceptualisation, nor does it use energy security indicators, but it refers consistently to security as one of its primary aims. We argue that the ambiguity of the concept plays a function in the policy process and is only seen as a problem in the academic literature. Building on the uncertainty literature, we conceptualise ambiguity as the type of uncertainty that emerges from complexity. Complexity leads to the existence of multiple representations of a system, which may serve different purposes in the policy process, generating ambiguity. Uncertainty is mobilised to frame energy policy as a matter of security. This has implications for the science-policy interface: on one hand, the analysis suggests that science's aim of providing holistic assessments and clarifications may not serve its desired instrumental purpose in policymaking; on the other, ambiguity allows for materially ineffective policy measures to persist in the name of energy security.

3.1. Introduction

Energy security has received growing attention in European Union (EU) and United States (US) public policy since the early 2000s, reviving a concept that had been predominant during the oil crises of the 1970s (Cherp and Jewell, 2011). While persisting as a priority in national agendas, its definition has evolved in time. Up to World War II, energy security was tied to the supply of fuels for the military (Cherp and Jewell, 2011), linking it to a military narrative. According to Walter Lippman, "a nation is secure to the extent to which it is not in danger of having to sacrifice core values, if it wishes to avoid war, and is able … to maintain them by victory in such a war" (Lippmann, 1943, p. 31). In other terms, the system is capable of preserving its identity. With the oil embargo of the 1970s, energy security became part of political diplomacy and geopolitical concerns. In this context, it referred to the risks of depending on oil imports, and on the vulnerability of oil trade to international diplomacy and political instability in producing countries. With the publication of the report "The limits to growth" (Meadows et al., 1972), security was also tied to the possibility of physical scarcity of non-renewable energy sources. Starting from the 2000s, the term has been increasingly associated with resilience based on a complex systems perspective (Cherp and Jewell, 2011), with the resource scarcity narrative based on concerns for the depletion of fossil fuel reserves (Sovacool et al., 2011), and with renewable energy based on the challenges of a renewable transition (Hughes, 2009; Månsson et al., 2014; Umbach, 2010). Challenges and solutions offered by specific primary energy sources, such as gas, coal, uranium, shale gas and variable renewable sources have also contributed to the proliferation of definitions of energy security.

In the EU, security concerns became central to the energy policy agenda following the 2005-09 gas and oil disputes between Russia and Ukraine, and between Russia and Belarus (Vahtra, 2009). As the electrification of energy systems gradually increases to incorporate a higher share of renewable energy, energy security has also evolved to incorporate dimensions that are unique to electricity, such as the security of transnational grids (Moore, 2017). The reintroduction of energy security in policy agendas has sparked academic debates that can be grouped under the field of energy security studies. The view that energy is a key input to all economic processes is widespread in these studies (Bielecki, 2002; Ciută, 2010), and in disciplines such as ecological economics (Georgescu-Roegen, 1971; Hall and Klitgaard, 2012; Smil, 2010). Characterisations of energy security range from the availability of primary energy sources (Bielecki, 2002), to the stability of internal markets (Yergin, 2006), to the affordability at consumer level (Sovacool et al., 2011). While availability and affordability are the two dimensions most commonly associated with the term (Bielecki, 2002; Jun et al., 2009; Leung, 2011; Sovacool et al., 2011; Sovacool and Brown, 2010; Yergin, 2006), it has also been linked to a number of other aspects, including for example sustainability (Sovacool et al., 2011), sovereignty and resilience (Cherp and Jewell, 2011). The ubiquity of energy security, and its context-dependent nature (Chester, 2010; Leung, 2011), have been the object of a branch of security papers exploring the ambiguity of the concept. Ciută (2010) explains the multiplicity of definitions of energy security as a result of the fact that "energy security is a complexity model with interlocking segments and levels of interaction" (p. 132). Energy security studies recognise that the security of modern energy systems has different characteristics than those attributed to the concept in the 1970s, among other factors because of the increased importance of renewable energy. They attempt to handle the multiple dimensions that are associated with this polysemic concept (Chester, 2010), which sometimes mixes technical and colloquial definitions of energy security.

From a policy perspective, the growing focus given to energy security in EU policy from the early 2000s follows a trend of securitisation of energy issues, i.e. "a process where governments frame energy as an existential threat to state interests" (Strambo et al., 2015, p.114). This is in contrast with previous framings of the 1990s, when energy had been mostly relegated to the technical domain, as highlighted by Kuzemko (2013) for the case of the UK. The importance of energy security in policy discourses, and the use of energy security justifications for disparate policy measures, is not new. This was best highlighted for the US by MIT economist Paul Joskow: "There is one thing that has not changed since the early 1970s. If you cannot think of a reasoned rationale for some policy based on standard economic reasoning, then argue that the policy is necessary to promote 'energy security'" (Joskow, 2009, p. 7). From a governance perspective, energy security is used both as a means to mobilise uncertainty and as a material issue. The multiple definitions provided by academia and the overflow of information do not lead to paralysis-by-analysis, as proven by the fact that the concept of energy security is recurrently used in policy. It is due to the very existence of multiple definitions that we may view energy security as characterised by ambiguity. Focusing at the interface between science and policy, there is a clear gap between the conceptualisations and measurements of energy security in academia, and the (non-)issue of ambiguity in policymaking (Sébastien et al., 2014).

Although some authors recognise that ambiguity plays a role in policy-making (Sovacool and Mukherjee, 2011; Stirling, 2007; Winzer, 2012), scientific literature largely sees ambiguity as a problem, aiming to reduce this type of uncertainty. Stirling (2007) argues that ambiguity is a type of uncertainty due not to lack of knowledge, but to the existence of "contradictory certainties". He submits that the real challenge at the science-policy interface is the failure to recognise this type of uncertainty and to reduce all scientific advice to risk assessment. However, this insight has fallen through, as scholars who analyse the science-policy interface still argue for reducing ambiguity. We argue that the role of ambiguity in governance is poorly understood and that reducing ambiguity may not always be functional in policymaking. This is in contrast with the predominant view that scientists should work towards the clarification of slippery concepts: Wellstead et al. (2018), for example, recognise that policy problems and solutions can be framed in different ways, leading to ambiguity, yet argue that scientists should take a normative stand and support a specific framing in order to reduce said ambiguity.

The aim of this Chapter is to contribute to a better understanding of ambiguity as distinct from other types of uncertainty, drawing from complexity theory. We use energy security as our empirical reference. We analyse and compare the multiple narratives of energy security in scientific literature and in EU policy documents, assessing the level of uncertainty associated with each representation. Even though energy security is recurrently described as an ambiguous concept, to our knowledge no attempts have been made at conceptualising ambiguity in this context, nor to theorise the role of ambiguity in energy governance. Because our contribution is primarily theoretical, we first develop a theoretical background that conceptualises ambiguity as the type of uncertainty created by complexity, and we discuss the implications of ambiguity for the science-policy interface. We use text analysis to identify the different types of uncertainty, including ambiguity, mentioned in scientific publications and EU policy documents. The results show the multiple scales of analysis used to define energy security and the types of uncertainty associated with it. Based on our results, we return to the discussion of how this type of uncertainty does not lead to paralysis in the policy process in the EU context, but rather provides a rationale for materially ineffective policy measures. We conclude by arguing that our finding about the (non-)issue of energy security definitions at the science-policy interface has theoretical implications for the role of ambiguity as distinct from other different types of uncertainty in policy processes, which requires a careful consideration of the limits of holistic assessments in guiding policy.

3.2. Conceptualising ambiguity

The ties between energy security and uncertainty are recognised by many authors. Energy security is recurrently linked to risk (Winzer, 2012), uncertainty (Kiriyama and Kajikawa, 2014) and ambiguity (Below, 2013; Chester, 2010; Ciută, 2010; Jansen and Seebregts, 2010; Jun et al., 2009; Kiriyama and Kajikawa, 2014; Leung, 2011; Sovacool and Brown, 2010; Sovacool and Mukherjee, 2011; Winzer, 2012). In this Chapter, we clarify the meaning of these terms by drawing upon the work of Knight (1921), Stirling (2003) and Wynne (1992) on uncertainty, and of Funtowicz and Ravetz (1994), Kovacic and Giampietro (2015), Strand (2002) and Zellmer et al. (2006) on complexity. Knight first introduced the distinction between risk and strict uncertainty in economics in his foundational work in the 1920s, defining risk as a situation in which the possible outcomes are known, and the probabilities associated with each outcome can be calculated. Strict uncertainty is defined as a situation in which the possible outcomes are known but the associated probabilities cannot be calculated. We speak of "strict uncertainty" to distinguish the technical definition of uncertainty from the general study of uncertainty, which includes risk, strict uncertainty, ignorance, indeterminacy and ambiguity. In the case of energy security, strict uncertainty can be associated with events such as price volatility (Winzer, 2012), and disruptive events such as tsunamis (Kiriyama and Kajikawa, 2014), which are known to occur, but cannot be precisely predicted. The novelty introduced by Knight is that uncertainty is conceptualised as a matter of degrees of (lack of) knowledge[10].

Building on the idea of degrees of uncertainty, Wynne (1992) identifies four types of uncertainty: (i) risk, in which the odds are known, (ii) strict uncertainty, in which "we know what we don't know", (iii) ignorance, in which "we don't know what we don't know", and (iv) indeterminacy or systemic uncertainty, in which "causal chains or networks are open". Ignorance in energy security may be associated with geopolitical threats derived from

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[10] Knight's definition of risk has been criticised in the literature for not taking into account "how people perceive uncertain phenomena and how their interpretations and responses are determined by social, political, economic and cultural contexts, and judgments" (Stirling, 2003, p. 237). The concept of risk is thus not fully captured by a technical definition of calculable probabilities and effects. Renn et al. (2011) criticize the reduction of risk to calculable probabilities for this concept may lead to the use of "technocratic, decisionistic and economic models of risk assessment and management" (p. 234).

“insecure political and unstable economic environments” (Zhang et al., 2013, p. 88), as well as with the emergence of new technologies, such as fracking, which introduce unforeseen opportunities and risks. Indeterminacy is associated with systemic changes. In the context of indeterminacy, uncertainty is irreducible, as systemic changes reduce the possibility of knowing. Stirling (2007) reorganises Wynne’s levels of uncertainty in a 2x2 matrix, which ranges from known to unknown outcomes and known and unknown probabilities, introducing ambiguity as an additional type of uncertainty. Once again, risk is defined as known outcomes and known probabilities, strict uncertainty as known outcomes and unknown probabilities, and ignorance as unknown outcomes and unknown probabilities. According to Stirling, ambiguity is defined as a situation in which probabilities are known but outcomes are unknown. The ambiguity of outcomes is not necessarily due to lack of knowledge, but to the fact that one cannot predict which of the known outcomes will be realised (Stirling, 2007), because of divergent and contested perspectives on the justification, severity or wider meanings associated with a perceived threat (Stirling, 2003). In their historical analysis of the evolution of energy security, Cherp and Jewell (2011) discuss how the concept has been used to pursue different outcomes. The concept of ambiguity thus suggests that uncertainty may be mobilised to pursue different goals, not because of a lack of information, but because a plurality of representations can be accommodated.

In the context of uncertainty, the linear model of science speaking truth to power is questioned, not only because science may produce incomplete knowledge, but also because social and political threats indicate that decisions cannot be reduced to rational, utility-maximising, get-the-facts-then-act models (Funtowicz and Strand, 2007; Pielke, 2004) Distinguishing between different levels of uncertainty is critical for decision-making. For example, after the Fukushima accident, experts declared that new designs for nuclear power plants took into account the risk of earthquakes (Diaz-Maurin and Kovacic, 2015). Better designs, however, do not solve the uncertainty linked to the unpredictability of earthquakes and tsunamis. Safer designs refer to advances in the reduction of operating risk at the level of the power plant. Strict uncertainty about earthquake forecasting (higher levels of uncertainty) cannot be factored into new nuclear designs. Importantly, the undistinguished reference to uncertainty with disregard to the type of uncertainty in question may create a false illusion of control, and a diffuse understanding of the role, and limits, of scientific knowledge in decision-making.

Stirling’s reference to open causality and unpredictability invokes complexity. Many authors have studied the implications of complexity for governance and public policy

(Funtowicz and Ravetz, 1993; Geyer and Cairney, 2015; Geyer and Rihani, 2012; Morçöl, 2013; Strand, 2002). In this literature, complexity is often defined in opposition to simplicity (Geyer and Rihani, 2012; Strand, 2002), and as a criticism of the instrumental understanding of the system to be governed through the lenses of reductionism, determinism, predictability and mono-causality. Positive definitions of complexity, however, are many and contrasting, as outlined in Chapter 1 of this thesis. It is worth re-iterating some of these concepts here, as they are central to the content of this Chapter. Strand (2002) distinguishes between thin and thick complexity, Geyer (2012) speaks of reductionist complexity, soft complexity and complexity thinking as a new epistemology of science, and Salthe (1993) provides five definitions of complexity ranging from measurable complexity to ontological complexity. Thin and reductionist complexity can be used as a means to recognise "reality" as differentiated and changing. A system is defined as complex if the whole presents emerging properties that cannot be inferred by analysing only the components of the system. In this case, complexity is also used to reject post-modernism (Cilliers, 1998), and to postulate the existence of a complex "reality" out there, whose complexity is independent of the observer.

Conversely, concepts of thick complexity and complexity thinking, as well as Salthe's insistence on the role of the observer in all definitions of complexity, create an understanding of complexity as a consequence of analytical choices as much as of what is observed (what has been referred to so far as relational complexity). In this view, complexity requires the use of multiple scales of analysis (Allen and Starr, 1982), so that both local rules of interaction between system components and emerging properties of the whole can be observed. The epistemology of complexity does not refer to knowledge *about* complex systems, but rather yields a relational understanding of knowledge as the correspondence between what is observed and what is modelled, building on Rosen's modelling relation (Rosen, 1991). For this reason, both Salthe (1993) and Kovacic and Giampietro (2015) refer to Peirce's semiotics (Peirce, 1935), the study of signs as a triadic relation between representation, application and interpretation of experiences. That is, knowledge cannot be separated from action. Rather than the study of systems "out there," complexity is the study of holons (Allen and Starr, 1982), that is, the relationship between (i) the knowledge generated, (ii) the choice of narratives defining causality between observables (Kovacic and Giampietro, 2015), and (iii) the choice of a temporal scale of the model, determining how knowledge is updated with experience (as an application of the knowledge itself) (Diaz-Maurin and Kovacic, 2015).

When it comes to governance, complexity theory is used by many authors to critique the use of reductionist science to guide decision-making (Geyer and Cairney, 2015; Geyer and Rihani, 2012; Morçöl, 2013). It is used to encourage more pragmatic, humble, reflexive and adaptive approaches to policy making (Geyer and Rihani, 2012; Kovacic and Giampietro, 2015; Strand, 2002). In line with our aim of conceptualising ambiguity and its role in governance, we build on the relational understanding of complexity as a means to critically re-think the implications of limited and contradictory knowledge for decision-making. Semiotics can be used to argue that science plays a role in the creation of emergent complexity (Funtowicz and Ravetz, 1993). For instance, through technology, scientific research is also a form of intervention in the world (Strand, 2002). We argue that the contribution of complexity theory to the science-policy interface should not be reduced to the type of science advice that can be derived from the concepts of emergence, non-linearity, open causality, self-organisation, etc. Geyer and Cairney (2015) correctly remark that these concepts are newish, as the messiness of policy making has been long studied in political science with no need of making reference to complexity. Rather, we submit that complexity theory is most usefully deployed in questioning the relationship between science and policy. Rather than speaking a more nuanced and complex truth to power, relational complexity makes it possible to analyse the mutual relation between science, scientific truths and power. The linear model relies on the rational use of scientific facts produced by supposedly neutral scientists. Questioning the linear model requires taking a critical stance also with regard to scientific facts and the role of experts.

In this context of complexity, the study of ambiguity may lead to insights about the role of experts. Building on Stirling's definition of ambiguity as a type of uncertainty, we conceptualise ambiguity as the uncertainty created by the existence of multiple non-equivalent representations of the same issue. Ambiguity is thus not just a matter of different opinions, as may be the case of the rise in the price of oil (perceived as beneficial by oil producers and problematic by oil importers). Instead, we argue that this type of uncertainty is caused by the existence of incommensurability in the knowledge base. That is, although a lot of information can be produced about energy security, there is no univocal way to combine these representations, as can be seen in the proliferation of energy security indicators (Jun et al., 2009; Sovacool and Mukherjee, 2011; Zhang et al., 2013) and of academic papers dedicated to the conceptualisation of energy security (Jansen and Seebregts, 2010; Winzer, 2012). The role of ambiguity in policy has been widely analysed in the literature (Funtowicz and Ravetz, 1990; Matland, 1995; Smith and Stirling, 2007;

Stirling, 2010; Zahariadis, 2008). According to Matland (1995), ambiguity is necessary to limit conflict (ambiguity of goals), and to define policy when there is uncertainty over the technology needed or over the role that various organisations are to play in the implementation process (ambiguity of means). With reference to the EU, Zahariadis (2008) explains that ambiguity is an integral part of the policymaking process in contexts where there is a plurality of often contrasting interests, a multiplicity and high turnover of actors, and highly bureaucratic systems that cause a fragmentation of the policy process.

Shackley and Wynne (1997) suggest that ambiguity may not only be preferred over knowledge in decision-making, but also provide more robust scientific tools than those generated by a precise knowledge base. Understanding the function of ambiguity in the policy process has important consequences for the interface between science and policy. Whereas numerous studies argue for more holistic and integrated conceptualisations of energy security (Cherp and Jewell, 2011; Kiriyama and Kajikawa, 2014; Sovacool and Mukherjee, 2011), Matland warns against the dysfunctional effects of clarity in policy implementation. Building on our analysis of energy security, we will return to the theoretical discussion of how ambiguity challenges the relationship between science and policy in the discussion section.

3.3. Materials & Methods

We use text analysis to identify the multiple representations of energy security across scales, and their level of uncertainty, both in scientific literature and in EU policy. As can be expected, scholarly articles focus predominantly on defining and measuring energy security, and policy documents focus on identifying different measures to increase energy security. For the academic literature review, twenty-three papers on energy security were analysed, published between 2002 and 2014. The papers are among the most cited on the topic, providing a comprehensive spectrum of how energy security is assessed in academia. They include perspectives from economics, engineering, geopolitics, policy, technology, political science, finance and geology, and were selected using citation indexes from Web of Science and the snowballing technique (Jalali and Wohlin, 2012). On the policy side, focus is given to the EU, which we chose as case study because (i) energy security has been part of EU policy since its inception (Cherp and Jewell, 2011; Ciută, 2010), (ii) many of the scientific articles analysed aim at informing EU policy (Bahgat, 2006; Costantini et al., 2007; Natorski and Surrallés, 2008; Umbach, 2010; Winzer, 2012), and (iii) energy security has been a high priority of the EU policy agenda since the 2008 gas crisis with Russia (Bahgat, 2006; Bielecki, 2002; Cherp and Jewell, 2011; Umbach, 2010; Yergin, 2006).

Three branches of EU documents are considered: the Energy Security Strategy (EC, 2014a), the Clean Energy for All Europeans package (EC, 2016b) and energy directives in force (EC, 2018a; 2018b; 2018c; 2019b). Additionally, the 2015 State of the Energy Union report (EC, 2015) is analysed. The aim of the policy analysis is to obtain an overview of the role played by energy security in EU policy, of which measures have been proposed as a means to increase security, of which issues are seen as problematic and of how uncertainty is handled. To this aim, the policy analysis includes press releases and fact-sheets (EC 2016d; 2016e; 2016f), as they can provide valuable insights into the underlying narratives surrounding energy security in EU policy.

The texts are coded for definitions of energy security and policy measures, scales and dimensions of analysis, as well as uncertainties, risks and ambiguities. The categorisation of energy security into different disciplines, domains, dimensions, pillars and principles is popular in the literature and these terms, often referring to different scales, are sometimes used interchangeably. Without delving deep into this categorisation, our interest lies in the different scales and types of uncertainty. The term scale is used here to refer to geographical dimensions (e.g., city, province, nation, region, world), temporal dimensions (short-term, long-term), and to hierarchical levels of analysis (energy system, energy sector, renewables, wind power, wind farm). There is no 1:1 mapping between geographical dimensions and hierarchical levels of analysis: the energy sector, for example, may refer to a specific country or to the global economy. This definition of scale is used to capture the multiple levels of granularity used in the literature to describe energy security. Having identified scales, definitions or dimensions (for academia) and measures (for policy) linked to energy security, the next section discusses the role that complexity plays in the energy security knowledge base, and the role that the ambiguity arising from complexity plays in policy.

3.4. Representations and uncertainties of energy security

Table 7 shows the text analysis results for the academic literature. The first two columns of the table refer to what was found directly in the text of each article, while the third column was added in order to discuss the multi-scalar character of the concept of security. The distinction between risks, strict uncertainty, indeterminacy and ambiguity follows the levels of uncertainty discussed in the theoretical framework. Our aim here is to show how the general argument for reducing uncertainty is applied indiscriminately to all types of uncertainty, including ambiguity. Stirling (2007) argues that whereas risk may be usefully described using scientific assessments, strict uncertainty and ambiguity require humility and the recognition of the limits of scientific knowledge. Limits are not to be confused with lack of validity. Rather, they are a request for more modest claims. Responding to our aim of theorising the role of ambiguity in policy processes, we will add to this argument and show that different types of uncertainty have different functions in the policy process.

Table 7. Definitions of energy security in the scientific literature

Paper	Framing (definition/dimensions) of energy security	Uncertainties	Scales
Bahgat, (2006)	Security defined differently w.r.t. price: "security involves achieving a state where the risk of rapid and severe fluctuation of prices is reduced or eliminated". W.r.t. technology: "Energy security depends on sufficient levels of investment in resource development, generation capacity and infrastructure to meet demand as it grows". W.r.t. to diversification: "Security of supplies can be enhanced by an overall diversification of supply".	**Risk:** In relation to price volatility: "In respect of price, security involves achieving a state where the risk of rapid and severe fluctuation of prices is reduced or eliminated". Risk of dependence. Threats can be geological or geopolitical.	Global, energy system Long-term
Bielecki, (2002)	Definition: "reliable and adequate supply of energy at reasonable prices"	**Risk:** "Short-term security covers the risks of disruption to existing supplies due to technical problems, extreme weather conditions or political disruptions. By contrast, the long-term security focuses on the risks that new supplies may not be brought on stream on time to meet growing demand"	Global, national Long-term, short-term
Cherp and Jewell, (2011)	Three perspectives: sovereignty (political science), robustness (engineering), resilience (economics/complex systems)	**Ambiguity** Energy security challenges are increasingly entangled so that they cannot be analysed within the boundaries of any single perspective	Global, national
Chester, (2010)	Six aspects: 1) risk management; 2) reliance on imports; 3) strategic use of the term; 4) its temporal dimension; 5) differences between energy markets and 6) how different actors have different perspectives on security	**Risk:** "the risk of interrupted, unavailable energy supplies; the risk of insufficient capacity to meet demand; the risk of unaffordable energy prices; the risk of reliance on unsustainable sources of energy. These risks may be caused by energy market instabilities, technical failures or physical security threats" **Ignorance:** "The meaning of energy security differs over the short, medium and long term because the probability, likelihood and	International, national Short, medium and long term

		consequences of different risks or threats to supply will vary over time.”	
Ciută, (2010)	Three logics: a logic of war for energy security (what states do war with/over), a logic of subsistence (energy need, complexity model of interacting parts) and a logic of ‘total’ energy security (ubiquity and reflexivity)	**Risk:** Can also be called “challenges” or “threats” and “vary from market failures and price volatility to investment risks, network disruptions and import dependency”. **Ambiguity:** “Energy security clearly means many different things to different authors and actors, and even at times to the same author or actor.”	Global and international, energy system
Costantini et al., (2007)	Refers to IEA definition “Energy security is defined as the availability of a regular supply of energy at an affordable price” and to the dimensions identified by the European Commission: physical, economic, social and environmental	**Strict uncertainty:** Makes the distinction between reserves and resources: the more the energy system depends on resources, the more uncertain it is. There is great uncertainty about oil supply from Middle East & Africa. Gas supply is less uncertain.	International, national, consumers Short-term and long-term
Hughes, (2009)	Refers to IEA definition: "the reliable supply of energy at an affordable price". 4 R.s: review of supply and infrastructure; reduce through conservation and efficiency; replace insecure supplies with secure ones through diversification and renewables; restriction of new demand	**Indeterminacy:** In many of the above examples, replacement policies that were introduced to improve energy security have, overtime, become energy-security problems in their own right. This reflects the temporal nature of replacement programs based upon finite supplies, from natural gas to agricultural energy crops.	Global energy market, energy system, consumer
Jansen and Seebregts, (2010)	Affordably and competitively priced, environmentally acceptable energy end-use services by the term energy services security (ESS)	**Strict uncertainty:** Resilience as a means to reduce uncertainty - “Enhancing societal resilience against long-term price volatility in the face of the strong inertia of national or regional energy systems”	National, regional, society, consumers Long-term
Jun et al., (2009)	"Energy security can be defined as a reliable and uninterrupted supply of energy sufficient to meet the needs of the economy at the same time, coming at a reasonable price"	**Risk and strict uncertainty** Related to reliability of supply Dependence of OECD countries on oil supplied from politically unstable regions; increasing energy demands worldwide for the next few decades in line with emerging economies and rapidly growing developing countries; increasing concerns for oil and other fossil fuel depletion, localized geopolitical instability	Global, international dynamics, national
Kiriyama and Kajikawa, (2014)	A shift from ensuring self-sufficiency of primary energy to diversification of secondary energy supply	**Risk and strict uncertainty:** Risks are quantified: “to appropriately assess the types of risk posed by hazards, we should consider essential societal changes— macro or micro, economic, political, social, environmental, scientific, technological, human health, etc.—taking into account future uncertainties.” **Ambiguity:** The degree of ambiguity “resulting from energy security being open to more than one interpretation when bibliometrics are applied” is quantified. Ambiguity here arises from the multiple perspectives of energy security literature.	National, energy system

Kruyt et al., (2009)	4 dimensions: availability (geological), accessibility (geopolitical), affordability (economical) and acceptability (environmental)	**Risk:** Supply and disruption risks, political stability risks, price movement risk **Strict uncertainty:** Uncertain reserves estimates	Global, international, energy system Long-term, short-term
Leung, (2011)	A supply-based definition for China, where the quest is for a "reliable and adequate supply of oil"	**Ambiguity:** ‘energy security’ is not a self-explanatory concept and researchers should formulate and contextualize it when applying it to a given country. “China’s current energy security measures aim at the quest for a ‘reliable and adequate supply of oil,’ but pay less attention to the maintenance of ‘reasonable prices.’ It is because ‘reasonable prices’ per se is an elusive goal and is judged by subjective criteria.”	National, energy system Medium to long-term
Månsson et al., (2014)	Security has evolved from meaning security of oil supply to including energy carriers. In industrialized countries, “energy security tend to be more closely connected to provision of energy access to the poorest in rural areas and, in urban areas, access for the rapidly expanding industry and service sectors”. Two dimensions: physical and economic	**Risk:** For the case of markets, makes the distinction between specific, systematic and systemic risk. Specific: diversifiable (unique to every exported and supply route); systematic: market risk; systemic: the risk of market collapse.	National, energy system, consumers, industry and service sectors
Natorski and Surrallés, (2008)	Security in the EU framed in terms of energy supply and dysfunctions in global energy markets	**Strict uncertainty:** “These observations were further aggravated by other uncertainties surrounding energy, such as the perspectives for global demand, price volatility, and the actual capacity of producer countries to supply the energy demanded due to the lack of necessary investments.” “Uncertainty could be further aggravated by natural disasters or other accidents having a negative impact on energy, especially on prices and accessibility”	Global, EU, national
Sovacool and Brown, (2010)	4 dimensions: availability, affordability, efficiency and environmental stewardship	**Ignorance:** Difficult to determine the extent to which countries are responding to ES challenges related to climate change **Ambiguity:** As a problem to solve: “This study provides precision, breadth, and standardization to the often ambiguous concept”	Global, national
Sovacool and Mukherjee, (2011)	5 dimensions: availability, affordability, technology development, sustainability, and regulation	**Ambiguity:** “The concept has become diffuse and often incoherent”. “Energy security is integral to modern society, yet its very ubiquity makes it prone to market failure and under-distribution”	Global, national, energy system Short and long term
Sovacool et al., (2011)	“How to equitably provide available, affordable, reliable, efficient, environmentally benign, proactively governed and socially acceptable energy services to end-users”. It has 5 dimensions: availability, affordability, technology development, sustainability and regulation	**Risk:** “The security of supply and the concentration of energy fuels among countries, theories about peak oil, rising prices, and energy poverty, to name only a few, have all become prominent concerns among policymakers and investors”	Global, national
Umbach, (2010)	Security as a geopolitical issue (security of supply)	**Strict uncertainty:** Of oil production, oil and gas reserves, of investments, of mid-term challenges, of reliance on gas imports	Global, EU Mid to long-term
Winzer, (2012)	"The continuity of energy supplies relative to demand"	**Ambiguity:** The concept is blurred, elusive, slippery, difficult to define, umbrella term	Global, consumers

		Risk and indeterminacy: “Threats like price volatility or marginal rises of global temperature can be seen as small changes in the sense that they have an impact on consumers but don’t change the way the system works. And threats like delivery disruptions or global warming of more than 2C can be seen as phase changes, because in addition to having a direct impact on consumers they also change the way in which the system works”	
Yergin, (2006)	The definition of security depends on the country: can be security of demand, control over strategic resources, concern over price changes, ability to adjust to new global markets, diversification, whether to build new nuclear plants, etc.	**Risk and strict uncertainty:** “The growth of Russia's output slowed substantially last year because of political risks, insufficient investment, uncertainties over government policy, regulatory obstacles, and, in some regions, geological challenges.” “The tens of billions of dollars required to bring the industry's output back up to its 1978 peak of 3.5 million barrels per day have not been invested both because of the continuing attacks on the country's infrastructure and work force and because of uncertainty about Iraq's political and legal structures and the contractual framework for investment” **Indeterminacy:** “Part of that challenge will be anticipating and assessing the "what ifs." And that requires looking not only around the corner, but also beyond the ups and downs of cycles to both the reality of an ever more complex and integrated global energy system and the relations among the countries that participate in it”	National, energy system
Yusta et al., (2011)	Energy has evolved from supply of affordable energy to a broader concept including: "price stability, diversification of energy resources, energy storage, economic investments, infrastructure protection, political and military power balance, geopolitics, homeland security, energy efficiency, energy markets, sustainability"	**Risk:** “The term ‘‘risk’’ refers to a combination of what can happen, how likely it is, and its consequences. The term ‘‘threat’ is more related to harmful acts to infrastructure. ‘Vulnerabilities’’ refers to the weakness level of a system to failures, disasters or attacks” “In case an emergency arises decision makers must understand the interdependences in the underlying infrastructure.”	Supranational, national, energy system
Zhang et al., (2013)	Related to import risks	**Risk:** Four dimensions relating to: external dependence (dependence risks), supply stability (supply risks), trade economy (economic risks) and transportation safety (transportation risks)	Global, international, energy system

In the articles that we analysed energy security is connected to multiple dimensions, from availability and affordability to resilience and technological development. These dimensions are linked to different scales, ranging from individual technologies to global economy, climate and reserves. While the term uncertainty is used indiscriminately in most articles, in referring to uncertainties here we use the classifications that were introduced in Section 3.2. Risk is the type of uncertainty that is more frequently discussed. Indeterminacy also appears, mostly linked to global resources and supply stability (Costantini et al., 2007; Jun et al., 2009; Natorski and Surrallés, 2008), price volatility (Jansen and Seebregts, 2010; Natorski and Surrallés, 2008) and natural disasters (Winzer, 2012; Natorski and Surrallés, 2008). The results of the text analysis of policy documents are shown in Table 8 (direct measures from the Energy Security Strategy) and Table 9 (indirect measures from all documents). The uncertainties reported in the tables are not mentioned directly in the policies but were identified based on the type of measure proposed. The ambiguity of energy security allows for a range of measures to be associated with it, resonating with Paul Joskow's words in the Introduction of this Chapter.

Table 8. Direct measures of energy security in the EU energy security strategy, their scales and uncertainties

Pillar	Measures	Scales	Uncertainties
1. Immediate actions aimed at increasing the EU's capacity to overcome a major disruption during the winter 2014/2015 (short term)	Enhance storage capacity, develop reverse flows, develop security plans at regional level, explore potential of LNG	EU, regional, forms of energy, energy system	Risk of disruption
2. Strengthening emergency/solidarity mechanisms including coordination of risk assessments and contingency plans; and protecting strategic infrastructure (short term)	Maintain minimum reserves of crude oil and petroleum products, invest in back-up infrastructure, physical protection of critical infrastructure, contingency planning/stress tests	EU, national, energy sector, forms of energy, energy sector	Contingency measures to reduce ignorance
3. Moderating energy demand (short term)	Speed up measures to achieve 2020 efficiency targets, focusing on buildings and industry	Building & industry sectors	Uncertainty of demand
4. Building a well-functioning and fully integrated internal market (medium to long term)	Discuss decisions at EU level, develop an internal electricity market, build key interconnectors	EU, electricity sector	Uncertainty of supply (market)
5. Increasing energy production in the European Union (medium to long term)	Increase renewables (which will require smart energy grids and storage capacity), carbon capture & storage	EU, national level, forms of energy, energy system	Uncertainty of supply
6. Further developing energy technologies (medium to long term)	Invest in energy research & innovation, financial instruments to leverage greater investments from industry	EU, national level	Technological uncertainty
7. Diversifying external supplies and related infrastructure	Strengthen relationships with existing suppliers, open the way to new sources, accelerate nuclear safety directive, ensure new nuclear plants do not depend on Russian fuel	EU, global, types of energy	Uncertainty of supply
8. Improving coordination of national energy policies and speaking with one voice in external energy policy	Build an energy union, include energy issues in political dialogues	EU	Ambiguity

Table 9. Indirect measures of energy security in EU energy policy and their scales, grouped under their uncertainties

Indirect measures	Scales	Uncertainties
Increasing diversification of sources, investment for a more secure grid, bioenergy, increasing diversification of supply from third countries, reducing energy imports, deployment of domestic sources, incentives to transmission and distribution operators, facilitating cross-border access to new electricity suppliers, renewable energy, decentralised energy production, biomass fuels converted into electricity and heat	EU, international, national Forms of energy, energy system	Uncertainty of supply
Energy efficiency, reducing gas imports through efficiency, decarbonisation of the heating & cooling sectors	EU, national Forms of energy, industrial sector	Uncertainty of demand
Regional co-operation	Regional and EU	Ambiguity
EU interconnections	EU, energy system	Technological uncertainty
Short term markets and scarcity pricing, a well-functioning and transparent energy market	EU, national, energy sector	Uncertainty of supply (market)
Achievement of EU energy and climate policy goals	EU, all economic sectors	Indeterminacy

Energy security is mentioned consistently throughout all EU energy policy documents analysed, although less so in the non-legal documents of the Clean Energy for All Europeans package, where, as the name suggests, focus is shifted to consumers. Direct measures range from technological ones, such as enhancing storage and reserve capacities, improving efficiency and building key interconnectors, to financial and political ones, such as investing in energy research and strengthening relationships with existing suppliers. Similarly, indirect measures touch upon most areas of interest to EU energy policy, from efficiency and decarbonisation to bioenergy and regional co-operation. In both science and policy, the concept of energy security is based on the interdependence between different hierarchical levels of analysis and the external-internal observation duality. Energy security is framed as the combination of (i) security of supply (availability and reliability), and (ii) security of demand (affordability).The need to match supply and demand requires handling the interplay of constraints posed by elements external to socio-economic systems, such as the availability of fossil fuels, solar radiation, water courses, and elements internal to socio-economic systems, such as geopolitical concerns, import dependencies, diversification of suppliers, transportation, infrastructure, technologies, distribution and accessibility issues, and price volatility. The external-internal duality permeates energy security definitions. Demand issues refer to the distribution of resources at a global, regional and national scale with regard to energy markets, infrastructure and economic sectors, and at the individual level with regard to consumers. Despite the ambiguity of the concept highlighted in the literature, energy security remains an important priority in EU policy. This finding is consistent with the study of the use of energy security in the UK (Cox, 2016). The next sections dig deeper into the implications of ambiguity for science and for policy.

3.5. Discussion

We start our discussion highlighting the distinction between ambiguity and vagueness in EU energy policy; then, implications of ambiguity and complexity for energy security are discussed. We end this section by discussing the wider implications of our findings for the science-policy interface.

3.5.1. Ambiguity and vagueness in EU energy policy

A distinction should be made between ambiguity and vagueness in the policy documents. Ambiguity is the uncertainty that emerges from complexity, while vagueness refers to the lack of clarity or specificity with which a term is used. Examples of ambiguity include the definition of energy efficiency, which is linked to a plurality of accounting methods. According to the directive, "energy efficiency means the ratio of output of performance, service, goods *or* energy, to input of energy" (EC, 2018c, p. 10) (our emphasis). The metrics used to measure services (e.g., contribution to GDP) and energy (e.g., MJ) are not equivalent to each other and generate ambiguity in energy efficiency indicators. Ambiguity is also present in target setting procedures: "Each Member State shall set an indicative national energy efficiency target, based on either primary or final energy consumption, primary or final energy savings, or energy intensity" (EC, 2018c, p.12). Vagueness can be seen in the renewable energy directive of the EU. For instance, the sustainability requirement is defined as: “Biofuel production should be sustainable. Biofuels used for compliance with the targets laid down in this Directive, and those that benefit from national support schemes, should therefore be required to fulfil sustainability criteria” (EC, 2018b, p.23).

Both ambiguity may be useful in policy processes, and may help generate consensus, but vagueness is a political decision (e.g., the term energy security is used in relation to geopolitical concerns to avoid explicit mention of specific countries and regions, to which different member states may have different relations), and ambiguity has to do with incommensurability in the knowledge base and the governance of uncertainty. Ambiguity makes it possible for a plurality of knowledge claims to be taken into account, extending the political space. It should be noted that, although the framing of ambiguity is very different in policy and in science, the uncertainty that arises from the presence of multiple perspectives is seen as problematic in some instances also in the policy realm. For example, a high priority for the EU is the coordination of national energy policies, as expressed by the idea of building an ‘Energy Union’ and including energy security in political dialogues. According to Natorski and Surrallés (2008), “attempts to frame energy as a security issue in order to gain support for a Common Energy Policy have been of limited effect, precisely because the security framing contributed to the further legitimisation of EU member states’ reluctance to cede sovereignty in the energy domain” (p. 71). This policy measure can be interpreted as the pursuit for the explicit discussion of topics otherwise left vague and ambiguous. Following Matland (1995), this instance can be interpreted as a case in which ambiguity of goals is accepted (energy security), in order to reduce ambiguity of means (coordination is needed).

3.5.2. Implications of complexity and ambiguity for energy security

The more one digs into the materiality of energy security, the more trade-offs, bottlenecks and lock-ins emerge. With reference to the nuclear power industry in France, Hecht (2018) argues that policy effectiveness relies on material effectiveness. That is, the ability to deliver on material changes legitimizes policy, and the use of scientific evidence. In the case of energy security, this relationship seems to lean not on effectiveness but on uncertainty. Material effectiveness is elusive in the context of complexity because of non-linearity and open causality. Comparing the current state of the EU’s energy system with the measures in EU documents, it becomes clear that (i) some energy security measures play minor roles in the overall energy system, neglecting larger lock-ins, and can be better understood as performing a symbolic role; (ii) measures targeting different components or stages of the energy system may generate important trade-offs and systemic changes. For example:

- Technical security: increasing renewables may present challenges for electric grid control due to the higher penetration of variable sources into the electricity system (Boyle, 2007).
- Market security: a higher integration of renewables in the electric grid may also lead to increased prices for consumers due to feed-in-tariffs. In Germany, for example, a higher renewable electricity generation led to lower prices for electricity producers and higher prices for consumers (Paraschiv et al., 2014).
- Nexus security: biofuels may increase energy security but pose threats to food security, as documented extensively in the literature (see, for example, Naylor et al., 2007).
- Geopolitical security: decreasing reliance on imports may decrease security threats caused by geopolitical issues, such as the Russian gas halts, but may also reduce diversification of supply routes and sources, making the system more vulnerable in times of unexpected crises. This is referred to as import availability (Månsson et al., 2014).
- Environmental security: domestic production of energy carriers may increase local environmental impacts, such as water contamination.
- Technological security: increasing the use of nuclear power may improve the security of electricity supply but pose other concerns, both of plant security and uranium dependence.

Many of these trade-offs are acknowledged in the policy documents analysed. Energy directives mention grid control problems caused by the increase in renewable energies, the dependence on fossil fuels for transport, and the possible impacts of biofuels on food production (EC, 2018b). The recurrent reference to risks, threats and urgency are means through which the lack of effectiveness in energy governance is recast as a security challenge. We argue that uncertainty (in the form of risk, strict uncertainty and indeterminacy) is mobilised to frame energy governance in terms of security. In this context, the use of a plurality of policy measures, and the inconsistencies or trade-offs that arise from such plurality reinforce the uncertainty element of energy security. Ambiguity is thus functional to this mode of governance, and the multiple representations that are produced by the scientific knowledge base reinforce the construction of energy security as a challenge of uncertainty, which requires governing. Ambiguity in this context makes it possible to avoid a paralysis in decision-making due to higher level uncertainties. Crucially, it also makes it possible to form uniformly group justifications and targets. Energy security is almost always bundled up within a mix of justifications which tend to include climate change and economic growth, as can be seen for example in the recast Proposal for a Renewable Energy Directive: "Moreover, renewable energy is also emerging as a driver of inclusive economic growth, creating jobs and reinforcing energy security across Europe" (EC, 2018b, p.1). Here, ambiguity is used both to group measures together (ambiguity/vagueness of means), and to group targets such as security and economic growth (ambiguity/vagueness of goals).

3.5.3. What does ambiguity imply for the science-policy interface?

Clarifying the concept of energy security would mean showing inconsistencies between representations, indicators and associated measures. Therefore, reducing ambiguity may make scientific advice less useful to governance. This observation runs counter to some of the ethos of science for policy, which is manifested in the goals of increasing clarity (Sovacool and Mukherjee, 2011), providing a holistic view (Kiriyama and Kajikawa, 2014; Sovacool and Mukherjee, 2011), putting boundaries on the term (Winzer, 2012), distinguishing between different logics of energy security and investigating their political and normative consequence (Ciută, 2010). A recurrent recommendation is that uncertainty should be analysed and communicated (Hughes, 2009; Yusta et al., 2011; Zhang et al., 2013). The results presented here, however, suggest that the communication of uncertainty at the science-policy interface needs to take into account what type of uncertainty one is dealing with. While risks, indeterminacy and ignorance are flagged as problematic in policy, ambiguity plays a different role. Before aiming to reduce ambiguity, it is important to take into account which policy processes may be affected, and even disrupted, by reducing ambiguity. Matland (1995) argues that ambiguity is a means to reduce conflict and hold together coalitions. The use of energy security as a recurrent justification for a wide range of measures indicates that the term is used to form coalitions or mobilise existing ones. Meritet (2007), for example, highlights how energy security measures and discourses in France are very different to other EU countries, given the role played by nuclear power. Ambiguity thus helps maintain coherence at the EU level, glossing over national differences.

The analysis of the role of ambiguity in policy processes shows that ambiguity is not a deficit of knowledge, and that therefore it is not a matter for scientific experts to "solve." These considerations open the debate about the role of science and science advice to policy in the context of complexity and uncertainty. Policy recommendations in the energy security literature are varied, ranging from "the institution of a consultative process towards broadly accepted (…) fuel-specific premiums" (Jansen and Seebregts, 2010, p. 1662), the provision of a detailed analysis of risk (Zhang et al., 2013), and definitional clarity (Chester, 2010), to the support of "multilateral approaches and concrete cooperation models" (Umbach, 2010, p. 1239), "anticipating and assessing the 'what ifs'" (Yergin, 2006, p.82), diplomatic and economic dialogues (Bahgat, 2006). While we are sympathetic to these suggestions, we refer to relational complexity to argue that through ambiguity, multiple knowledge claims and multiple sources of expertise are brought to bear on the policy process. Policy is informed not only by scientific evidence, but also by political, economic and social considerations. Ambiguity makes it possible to maintain a dialogue with a wide range of actors, including but not limited to scientific experts. We argue that it is important to take into account who would benefit and who would loose from the clarification of ambiguity, and to assess what is at stake behind different uses of the term.

3.6. Conclusions

In this Chapter, energy security is used as an entry point to theorise the role of ambiguity in governance. Energy security is an ambiguous term, with many competing and contradictory definitions. We used complexity theory to argue that the multiple definitions refer to non-equivalent representations of energy security and cannot be reconciled or unified without losing relevant information. A text analysis of academic publications and policy documents was conducted to compare which types of uncertainty are mobilised, with a particular focus on ambiguity, defined as the type of uncertainty arising from complexity. Many authors have focused on reducing the ambiguity of definitions of energy security and have provided broad definitions that can capture is multiple facets (Sovacool and Brown, 2010; Winzer, 2012; Jansen and Seebregts, 2010; Jun et al., 2009). On the other hand, the definition of energy security does not necessarily arise as a problem in EU public policy. This incongruence between science and policy is not a problem per *se*. Academia has different interests than policy, and what can be interesting from a research perspective (conceptualising an ambiguous term) may not be a priority in policymaking. Moreover, the interactions between science and policy are rarely direct (with scientific evidence guiding policymakers), and the effects of conceptualisation literature can be diffuse (Ciută, 2010), in helping to advance a field that may eventually have impacts on policies. Since we relied only on secondary information through text analysis, the differences in the treatment of ambiguity between science and policy would benefit from further research based on primary data through, for instance, interviews with both scientific experts and policymakers.

The results and discussion suggest that it is important to pay attention to what is at stake before clarifying ambiguities at the science-policy interface. This critical reflection should by no means be understood as a call for irresponsible politics or post-factual decision-making. Rather, it is important to understand the "network of artefacts, knowledges and institutions" (Shackley and Wynne, 1997, p.257) that constitute energy governance before prescribing good practice. To this purpose, we rely on a relational understanding of complexity, which relates representation to the institutions and the uses of knowledge. Returning to the debate raised by Wellstead et al. (2018) about the need to reduce ambiguity, we argue that from a complexity point of view, reducing ambiguity would entail (i) a normative choice of some scientific facts over others, and (ii) a poor understanding of how plural and ambiguous knowledge is used in policy processes, which would widen the gap between science and policy, rather than closing it. In contrast, discussing the role of ambiguity in policy can help manage and understand this gap.

Chapter 4

Are electric vehicles the answer? How policy narratives shape the framing of complex sustainability problems

Narratives are necessary devices used by observers to make sense of complex reality. This chapter presents work that is currently under review, focusing on the multi-level narratives underpinning policy documents (Di Felice et al., *forthcoming*). Policies are shaped by stories about what measures should be implemented, how they should be implemented and why they should be implemented. We introduce a relational narrative taxonomy aimed at mapping these narratives in policy documents. We use this taxonomy to ask why the EU wants to push for an electric vehicle transition. Through a content analysis of policy documents, we find that a transition to electric vehicles is justified through promises of a reduction in greenhouse gas (GHG) emissions and oil imports, as well as positive impacts on citizens (through reduced pollution) and the economy (through a boost in manufacturing and the generation of jobs). We check the coherence of these narratives by critically reviewing the existing knowledge base. Our results show that the circle of promises surrounding electric vehicles is uncertain. Positive economic impacts largely depend on the location of battery and car manufacturing; GHG emission reductions depend on promises of decarbonisation of the electricity sector, as well as on driving behaviours; crude oil imports may be replaced by lithium, cobalt and or battery imports; reduced tailpipe pollutants may be counterbalanced by increased pollutants at electricity production sites. These uncertainties do not weaken the strength of the techno-optimist imaginary associated with electric vehicles. We suggest that science has a part to play in building alternative imaginaries, shifting away from the model of private vehicular use.

4.1. Introduction

We don't know whether electric vehicles (EVs) will replace internal combustion engine vehicles (ICEVs). Likewise, we don't know what the consequences of that replacement would be. Other things being equal, greenhouse gas (GHG) emissions would likely decrease, though that decrease is predicated on how and where electricity is produced, on how and where batteries are produced, on how long batteries last and on how they are recycled. Still, "other things" are not equal when innovations become commonplace, and we don't know what effects the mass implementation of EVs will have on driving patterns, on the use of public transport, on other behaviours outside of transport, on imports, on oil prices or on the electric grid. This unpredictability is not unique to innovations nor to sustainable mobility. Rather, it is characteristic of the futures of complex systems. From an epistemological perspective, it is impossible to generate a single correct representation of something complex (Rosen 1991; Mayumi and Giampietro 2006; Zellmer et al 2006; Allen et al 2017). This statement does not mean that "anything goes" or that all representations of possible futures are equally valid and equally likely (Stirling, 2010; Parker 2006; Mitchell 2009). It means that representations of the future inevitably rely on normative assumptions (Bergman et al., 2017). This challenges the linear model of science speaking truth to power (Hoppe 1999; Funtowicz and Strand 2007), as we are forced to ask: whose truth?

Faced with complex sustainability challenges, policies simplify reality by fitting it within a chosen storyline. This framing leads to the elimination of alternative storylines and to the normalisation of dominant policy discourses, particularly techno-optimist ones (Wynne, 2005). This process is not good or bad per se: simplification of reality is necessary for decision-making. The question is whether chosen simplifications are adequate in addressing the problems they wish to tackle. In addition, the web of narratives and power relations framing a policy solution as being desirable determines what role is played by the knowledge produced around different solutions. In this Chapter, we use the case study of EVs to introduce a relational narrative taxonomy, aimed at systemically highlighting the types of policy narratives that frame dominant policy solutions. We make the distinction between three types of narratives in policy documents: normative narratives (what is the desirable policy measure?), justification narratives (why is it desirable?) and explanation narratives (how should the measure be implemented?). The multi-scale narrative taxonomy allows us, then, to organize existing knowledge about EVs, focusing on the normative-justification relation. We check whether the normative narrative, that EVs are desirable and should replace ICEVs, is coherent with its justifications, which include positive economic impacts, GHG emission reduction, citizen wellbeing and security. Coherence is discussed by reviewing existing studies and reports addressing these domains, while also discussing the uncertainty in the knowledge base, and the role it plays in the context of policy narratives. There is, in fact, great uncertainty in the EV knowledge base. This situation does not seem to be significantly improving as more studies are generated. For example, a study by Tagliaferri et al (2016) noted that the energy required for battery manufacturing can, depending on chosen assumptions, vary by two orders of magnitude.

Assessments of how EVs compare to ICEVs in terms of GHG emissions have been shown to strongly depend on the electricity mix (Moro and Lonza 2017; Girardi et al 2015), extraction and manufacturing processes (Hawkins et al., 2013), temperature, driving behaviour and patterns (Yuksel et al., 2016), vehicle weight (Nealer and Hendrickson, 2015), battery lifetime (Ellingsen et al., 2016) and end-of-life disposal (Hendrickson et al., 2015). Projections of EV uptake rates and economic impacts are also difficult. Due to changing estimates of EV uptake, medium- and long-term projections of overall electric grid demand produced by the United Kingdom's National Grid plc fluctuated, for example, twofold between 2017 and 2018 (National Grid, 2018, 2017). Estimates of lithium availability and bottlenecks also remain uncertain, depending on how one measures existing reserves (Vikström et al., 2013) and on whether lithium quality is taken into account (Narins, 2017).

Nevertheless, uncertainties and nuances associated with EV futures have not tarnished their image in policy discourses. Wentland (2016, p. 287) explains that "the more an innovation is characterized by an intricate 'circle of uncertainties' (Rammert 2002, p. 176-78), the greater the influence of relatively abstract visions becomes in the process of technological and organizational selection". Policies rely on imagined futures (Bergman et al., 2017). By identifying, mapping and discussing EV narratives in EU policy, we visibilize the epistemic box within which the policy measure is being proposed, opening the space to question it.

4.2. Narratives in policy

Narratives are stories that are told to make sense of complex realities. Stories call for a string of causality connecting events to one another. In doing so, they highlight which events are relevant within a specific framing. For example, levels of soil acidity are mostly considered irrelevant in discussions of sustainable road transport. The adoption of narratives is unavoidable when modelling and explaining events. Policies are grounded in narratives, as they build on models and explanations. However, the landscape of possible narratives and the mechanisms that lead to the dominance of certain narratives over others become invisible when preferred narratives are normalised, eventually become truisms. For example, there is little question in EU sustainability policies about whether reducing GHG emissions is good or bad. To discuss types of narratives in policy documents, we make the distinction between normative narratives (what is a desirable solution to be achieved by policy?), justification narratives (why is this solution desirable?) and explanation narratives (how should this solution be implemented?). Normative narratives are rarely stated explicitly in policy documents, since by the time a solution enters the policy space its normative assumptions are usually taken for granted (e.g., it is taken for granted that EVs are desirable and should replace ICEVs).

Instead, policies mostly focus on the *normative-explanation* relationship: given an accepted policy solution, with its associated set of (unquestioned) justifications, policies aim at introducing mechanisms to enforce the solution. Similar to our justification narratives, in discussing the role of narratives in EU policy, Felt et al. (2007) refer to the concept of master narratives, i.e. relatively abstract narratives that operate at the highest, normative level. Master narratives are associated with visions of the future that “are malleable, allowing enactors to avoid discussing technical details that may expose the contested nature of their own agenda” (Sovacool et al 2019, p. 172). Differently from this definition, our narrative distinction is relational: there are no justification narratives in absolute terms, but only insofar as they justify a specific policy solution, in the form of a normative narrative. As shown in the right panel of Figure 9, the relationship between justification narratives, normative narratives and the policy-relevant knowledge base is sustained by two self-reinforcing loops. In particular, justification narratives of techno-optimist nature generate dominant technological policy solutions.

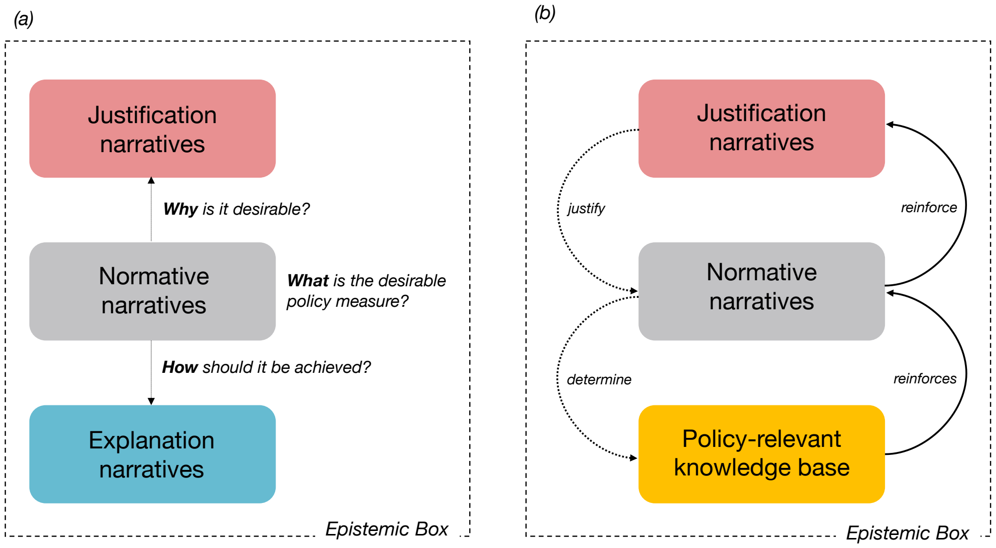

Figure 9. Triadic relationship of narratives in policy (a): Relationship between justification narratives, normative narratives and explanation narratives (b) Relationship between justification narratives, normative narratives and the policy-relevant knowledge base

EVs, biofuels and other alternative fuels are examples of this process in the context of sustainable mobility, a process by which solutions contribute to the validation of their own justification narratives. The more biofuels are proposed as a solution to diverse policy objectives, for example, the more their justifications become dominant, thereby colonising future imaginaries through what Berti and Levidow (2014) call a "policy-promise lock-in". The second loop links technological policy solutions to the policy-relevant knowledge base. More and more, scientists are asked to produce policy-relevant results. However, when research agendas are reduced to the assessment of policy options that have already been determined within a chosen set of justifications, research itself, in an attempt to produce results that are considered relevant for policymaking, runs the risk of presuming those same narratives. This problem was identified as early as 1945 by Merton, who made the distinction between 'unattached' intellectuals and 'bureaucratic' intellectuals.

When producing policy-relevant research, the latter must "think in technical and instrumental terms of ways of implementing a policy *within a given situation*" (Merton 1945, p. 412). As introduced in Chapter 1, we refer to this "given situation" as an epistemic box, i.e., the space where policy solutions are generated within justification narratives, and research is produced to analyse these solutions, carrying a set of often undisclosed assumptions about what is desirable, and for whom. Mapping narratives through a relational scheme allows producing and organising scientific information for different purposes. The explanation-normative relationship can be explored by checking whether concrete policy measures actually reach their desired goals (e.g., do more charging points lead to more EVs?). Shifting to a higher level of analysis, we focus here on the normative-justification relationship (do EVs fulfil their promises?). At a more abstract level, this allows us to also question the coherence among justification narratives themselves (can these promises be simultaneously fulfilled?).

4.3. Methods

We performed a content analysis of EU policy documents and identified justification and explanation narratives across two levels: first at the level of low-emission mobility, then focusing specifically on the solution of EVs. Our content analysis built on the principles of grounded theory (Walker and Myrick, 2006). First, relevant policy documents were selected. We selected documents authored by the European Commission and published between 2009 and 2019, excluding sustainable transport documents that were not concerned with road transport, as well as those documents that focused on a specific measure or issue unrelated to EVs, such as policies on road safety and traffic offences. Our document selection was biased towards the policy solution of alternative fuels and EVs, as we did not aim to comprehensively compare all sustainable transport policy solutions[11].

The process of moving from policy documents to narratives and their interrelations built on three steps, the first of which was open coding. During this deductive phase, the main codes used to identify narratives emerged from an initial screening of the texts. Through a second screening, a mixed deductive and inductive step termed axial coding, initial codes were refined as the texts were coded. Finally, the codes were interpreted—their relationships were given meaning and were used in the development of a theoretical framework, i.e., the narrative taxonomy described in the previous section. In this way, the theoretical framework itself was developed in tandem with the coding procedures, and the boundaries between data collection, analysis and framework construction were blurred. A list of the hierarchy of nested nodes used in the content analysis is shown in Figure 10.

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[11] A full list of the selected policy documents can be found in the Appendix A2, Table 13

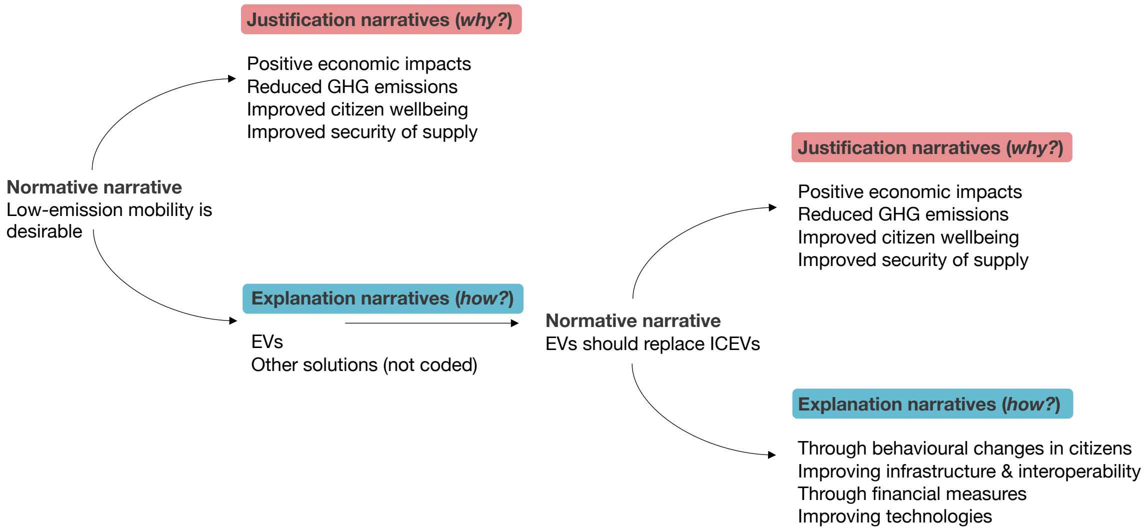

Figure 10. Content analysis codes (main clusters)

The Figure shows the relational approach to the narrative taxonomy: the low-emission mobility package (centred around the normative narrative that a low-emission mobility is desirable) was associated with a set of justification and explanation narratives, including EVs (answering the question: How should a low-emission mobility transition be implemented?). Then, when focusing on EVs, the explanation narrative (i.e., that EVs can contribute to a low-emission mobility transition) became a normative narrative, associated with its own set of justifications (answering the question: Why are EVs desirable?) and explanations (answering the question: How should EVs be implemented?). In the interpretation phase, clusters of justifications and explanation were further split into sub-clusters (not shown in Figure 10). While clusters of justifications are the same for low-emission mobility and EVs, sub-clusters differ. The second phase of the analysis used the existing knowledge base to selectively comment on the main narratives found in the first phase. This step can be seen as an inductive literature review, looking for information on specific angles and debates surrounding EVs in the most comprehensive and impactful studies of recent years[12].

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[12] Further information on how the studies were selected is included in the Appendix A2, Table 14

4.4. Results

4.4.1. Low-emission mobility narratives

The justification and explanation narratives associated with the normative narrative that low-emission mobility is desirable are shown in Figure 11. The role played by transport as a prime energy consumer and polluter, as well as a prime mover of the economy, is stressed throughout the policy documents. Oil imports are a problem from an economic perspective, with price hikes of oil supply damaging the economy, and from a security perspective. In this context, a transition to low-emission mobility is promising. According to EU policy, transport is a pillar of the economy and low-emission mobility can enable economic recovery and economic growth, creating jobs and contributing to a circular, low-carbon economy. The positive effects that a low-emission mobility revolution can have on citizens are multiple, centred around reduced air and noise pollution, leading to healthier environments and disease reduction.

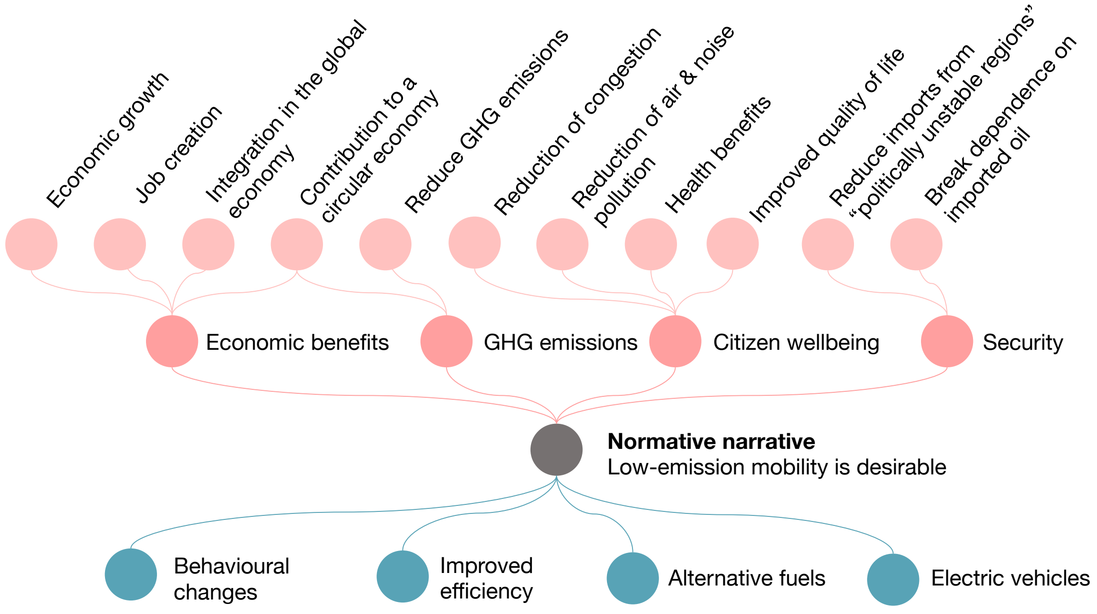

Figure 11. Low-emission mobility narratives. Justification narratives are grouped under four clusters and then expanded into sub-clusters (pink nodes). Explanation narratives are grouped under four clusters (blue nodes)

This better quality of life is not associated with a reduction in mobility: curbing mobility is "not an option" (EC, 2011, p.5). Reducing the number of cars on the street, or the number of trips taken by car vs. those taken with other transport modes, is not discussed. The transition relies on four solutions (explanation narratives): behavioural changes, increased efficiency, alternative fuels and electro-mobility. In Figure 12, we focus on electro-mobility[13]. The explanation narrative to low-emission mobility becomes a normative narrative (i.e., EVs should replace ICEVs), with its own set of justification narratives above, and explanations below. From the EU policy perspective, the potential that EVs have is strong. They can boost manufacturing, leading to economic growth and job creation, reduce oil dependence, reduce GHG emissions and local pollution and improve citizen health. In terms of specific measures (explanation narratives), pushing consumers to make behavioural changes can contribute to the EV transition.

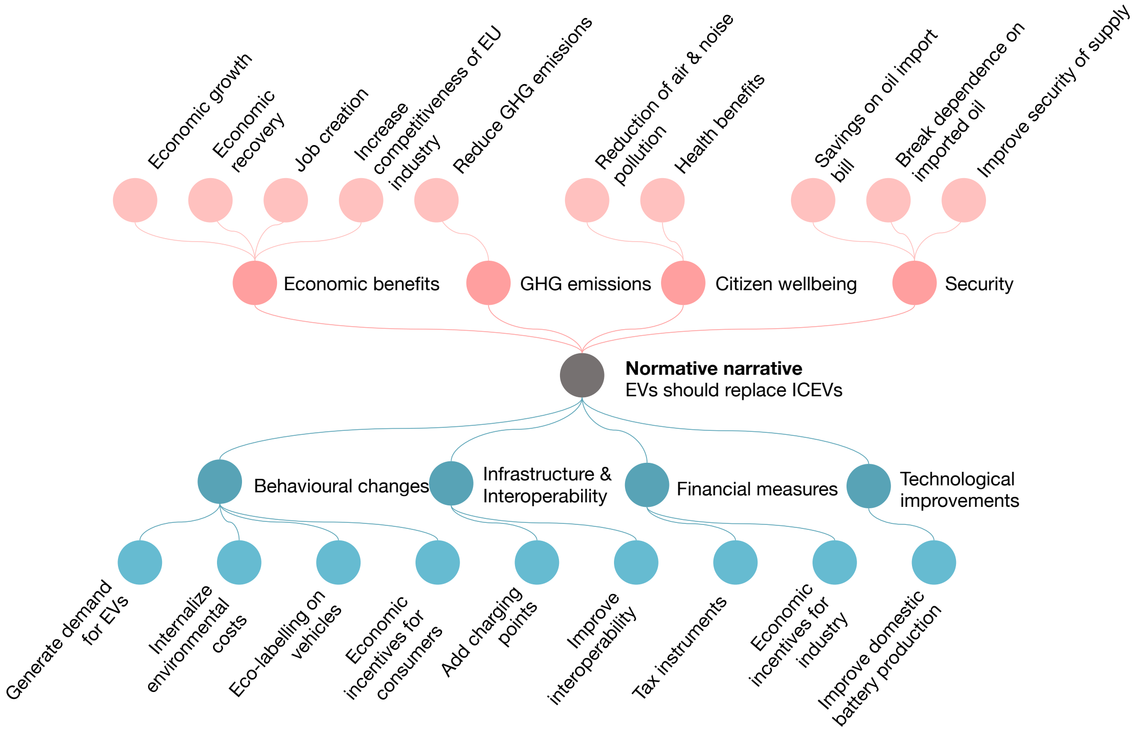

Figure 12. Electric vehicle narratives. Justification narratives are grouped under four clusters and then expanded into sub-clusters (pink nodes). Explanation narratives are grouped under four clusters and expanded into sub-clusters (blue nodes)

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[13] Details of narratives and their reference documents are included in the Appendix A2, Table 15

The change in this case is purely technological, with consumers framed as rational agents who will “make the right choice” once they are provided with the right information and right incentives. The predominant way to increase the number of EVs on the street is the addition of more charging points (the only measure backed by its own directive, (EC, 2014b)), which will ultimately lead to behavioural changes by reducing range anxiety. Other explanation narratives include providing economic incentives to industry and improving the domestic production of batteries. We address each cluster of justification narratives in the next sub-sections.

4.4.2. Economic benefits

In terms of frequency, the economic benefits of EVs are the predominant justification narrative. Economic growth through EVs is meant to be achieved by a boost in the automotive industry, generating new jobs and strengthening industry competitiveness. Projections of the potential economic impacts of an electro-mobility transition in the EU, however, remain uncertain. Manufacturing an EV requires, on average, more energy and less labour than an ICEV (Girardi et al 2015; Deloitte 2019). A report by the US Congressional Research Service suggests that with a shift to EVs “(…) fewer employees may be needed than at present because vehicle battery packs have relatively few components and are less complicated to assemble than internal combustion engine powertrains” (Canis 2019, p. 2). Still, the effects that a new technology may have on jobs are difficult to predict, and different jobs may be generated in a transition towards electro-mobility. A report by the European Climate Foundation argues that the loss of jobs in the automotive industry due to a transition to EVs will be greatly outpaced by new jobs generated, predicting that up to 1.1 million new jobs could be generated in Europe by 2020 and over 2 million by 2050 (Cambridge Econometrics, 2013). A more modest projection is provided by Transport & Environment (2017), where it is argued that even if 90% of all EVs are produced within the EU by 2030, this will still result in a net job loss in the EU. The likelihood of the EU producing 90% of the EVs sold within its countries by 2030 is low: in Germany, the EU country with the strongest automotive industry, only one in four EVs on the road is produced domestically (Schott et al., 2015). The manufacturing of battery packs is also almost entirely outsourced. In 2017 China, Japan and Korea produced almost 90% of the global lithium-ion battery stock (Lebedeva et al 2016; Chung et al 2016).

Beyond job creation, battery outsourcing links to broader narratives of decoupling energy consumption and environmental impacts. Since most of the GHG emissions associated with EV manufacturing are due to the manufacturing of batteries (Ellingsen et al., 2014), there may be a trade-off between job creation on one hand, and GHG emissions of the other. This also suggests that the origin of batteries should be taken into account when framing EVs as a low-emission solution, since the claim may or may not hold true depending on the energy mix used for manufacturing.

4.4.3. GHG emissions

EVs are a key component of the EU's decarbonisation strategy, promising to lower emissions of the transport sector. This promise hinges on renewable energy goals: as the EU aims to fully decarbonise its electricity grid, EVs are projected to produce zero emissions during their operational phase. For EVs to be fully zero-emission, the industrial and extractive sectors would also have to decarbonize, and not just the electricity grid. If we do focus solely on the electricity grid and on tailpipe emissions, projections for the future are contrasting. Many studies have modelled 100% renewable electricity scenarios for 2050 (see Pleßmann and Blechinger 2017; Bussar et al 2016; Capros et al 2014; Haller et al 2012, among others). Still, others have questioned the feasibility of a rapid decarbonization of the electricity sector (Renner and Giampietro 2020; Loftus et al 2015; Smil 2016;). The timing of a renewable transition is central to these critiques (Fouquet, 2016). Ultimately, modelled decarbonization pathways cannot tell us how long a renewable energy transition will take, and the possibility of a slow transition with unexpected bottlenecks must be taken into account, as well as the impacts that EVs have on GHG emissions given current electricity mixes. A review by Yuksel et al (2016) found that depending on regional factors, driving patterns in different US states, and vehicle size, PEVs may emit more or less than gasoline vehicles. The effects of vehicle size on GHG emissions were also assessed by Ellingsen et al (2016). The authors found that, taking the EU's average carbon intensity of approximately 500 g of CO_2 eq. per kWh, "larger EVs can have higher lifecycle GHG emissions than smaller conventional ones" (p. 7). A review by Nealer and Hendrickson (2015) also highlighted the role played by vehicle weight and lifetime, as well as driving behaviours.

Moving past the uncertain accounting of GHG emissions, existing literature on spillover effects suggests that technological comparisons do not paint the full picture when it comes to assessing the environmental impacts of EVs as a substitution to ICEVs. The Norwegian case, where EV uptake is the highest, hints at two risks. The first is that citizens buy EVs as second cars, thus not substituting ICEVs (Klöckner et al., 2013). The second is the risk that EVs may not simply substitute ICEVs, but also trips which would have been taken by walking, cycling or public transport (Holtsmark and Skonhoft, 2014). These results are shaped by specific policies and contexts and should not be generalized to other cases. However, they point to possible spillovers which should not be underestimated, and to the need of viewing the unsustainability of transport from a system, rather than solely technological, perspective.

4.4.4. Security and material requirements

Passenger cars are responsible for almost 40% of all of the EU's liquid fossil fuel consumption (Eurostat 2017; Löhr et al 2016), and 90% of these fuels are generated from imported crude oil (Eurostat, 2018). Security issues are also tied to geopolitics, as oil imports are from "politically unstable regions" (EC, 2013, p.2) and to the economy, with a crude oil import bill "estimated at around €187 billion in 2015" (EC, 2016b, p.6). The fact that the EU also imports most of its batteries seems to be more of a concern for industry competitiveness than it is for security, since partially shifting crude oil imports to battery imports contributes to a diversification of import types and sources. Still, the EU lacks the raw materials needed for batteries, i.e., lithium and cobalt. Interestingly, neither are mentioned directly in the analysed documents. In 2017, almost 60% of global cobalt production took place in the Democratic Republic of Congo (INSIDEEVs, 2019), where mining activities are notoriously tied to child labour (Faber et al 2017; Chohan 2018; Tsurukawa et al 2011; Banza Lubaba Nkulu et al 2018). Lithium reserves are also concentrated in few countries. In 2017 Australia, Chile and Argentina produced over 90% of the raw material (INSIDEEVs 2019), which is being dubbed "the new gold" given the geopolitical importance it is gaining not only for EV batteries but also for grid-level storage (Tarascon, 2010) and consumer electronics. Socio-environmental impacts of lithium extraction are under-studied and severe (Agusdinata et al., 2018).

The extraction of lithium in brine contaminates water and leads to environmental injustices (Romero et al., 2012) . As of February 2020, the Environmental Justice Atlas

(EJAtlas) lists twelve cases of environmental justice conflicts linked to lithium mining[14], of which eight take place in the Lithium Triangle, i.e., the part of the Atacama Desert shared by Chile, Bolivia and Argentina, where over 50% of global lithium reserved are estimated to be[15]. Local environmental impacts are mostly tied to the intensive use of water and to the generation of waste (Flexer et al., 2018). This points to the wider implications of sustainability policies in interconnected and globalized markets. Similar to how the EU is concerned with GHG emissions, which lead to global environmental impacts beyond the EU itself, mechanisms to include local impacts of extractive activities within decision-making should be taken into account, particularly when leading to trade-offs between sustainability in the EU and sustainability elsewhere.

4.4.5. Citizen wellbeing

EVs promise to improve citizen wellbeing through reduced noise and improved air quality, leading to health benefits. A critical review of the Norwegian case by Holtsmark and Skonhoft (2014) argues that noise reduction by EVs would not be significant, as tyres, rather than engines, are the main cause for noise pollution, depending on the speed of vehicles. Reductions in tailpipe emissions may be outweighed by electricity generation emissions, depending once again on the electricity mix. For the case of China, Ji et al., (2011) found that switching to EVs would lead to more local pollution than ICEVs, although in different areas. This is an extreme case due to China's coal-heavy electricity mix. Still, it suggests that the heterogeneity of EU countries should be taken into account when setting EV targets. Poland, for example, also has a coal-heavy electricity grid, meaning that other sustainable transport measures would likely be better suited to its context, at least until coal is phased out from its electricity mix. However, the trade-offs are not restricted to China and to countries with a coal-heavy mix. Buekers et al (2014) model the emissions of local pollutants from EVs under different electricity scenarios in Europe. They find that depending on each country's specific electricity mix, EVs may or may not lead to a reduction in local pollutants. For the case of the US, Holland et al (2016) argue that the vast majority (over 90%) of local pollutants associated with EVs are externalized,

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[14] https://ejatlas.org/commodity/lithium, accessed on February 4, 2020

[15] https://resourceworld.com/lithium-triangle/, accessed on February 4, 2020

i.e., not emitted where the car is actually driven. Assessing the external costs of EVs in Europe, Jochem *et al* (2016) find that overall improvements in air pollution are marginal and effects are widely externalized. Again, we see how the promise of EVs strongly relies on promises of a renewable electricity mix. Similar to what we mentioned for material requirements, this also suggests that local and global impacts of EVs beyond their operational phase should be considered.

4.5. Discussion & Conclusions

Transport systems are complex: they result from the interplay of infrastructure, politics and social practices, with each element affecting the others in impredicative ways. EVs are part of a wider imaginary of a techno-optimist transition. This imaginary includes technologies such as biofuels, electro-mobility, solar panels, efficient appliances, negative emission technologies and climate-smart agriculture. It does not include discussions on behavioural changes, such as the reduction of the number of cars per capita or a reduction of the number of journeys taken by car. The number of cars per capita in the EU has been growing consistently over the past ten years (Eurostat, 2020a). Over 80% of journeys are taken by car (Eurostat, 2020b). The techno-optimist imaginary, being inextricably tied to the mandate of economic growth, fails to challenge the model of private vehicular use (Marsden et al., 2014). When discussing the validity of justifications attached to EVs in policy documents, what emerges is nuance and uncertainty. The promises associated with EVs rely on other promises: that batteries and cars will be produced locally, that the electricity mix will be decarbonised soon and that their introduction will not lead to other unsustainable behaviours. However, trade-offs across scales and dimensions are inevitable. The positive effects of reduced oil imports, reduced operational GHG emissions and local pollutants, as well as potential increases in jobs, come with potential increases in lithium, cobalt and battery imports, with their associated socio-environmental impacts, a re-shuffling of emissions across different geographies, and a shift in job location dictated by mechanisms of the global market. As such, one effect may prevail over the other depending on myriads of assumptions (known knowns), i.e. vehicle size, as well as known unknowns (what will the electricity grid look like in 2030? what consequences will EVs have on other behaviours?) and, importantly, unknown unknowns (Pawson et al., 2011).

The role played by uncertainties in determining sustainability pathways depends on the power relations and justifications associated with normative narratives. The narrative taxonomy proposed in this paper allows mapping narratives in order to discuss who benefits from the justification, who loses, and which stories are left unspoken (such as the case of the socio-environmental impacts of lithium and cobalt extraction). At the level of EU justification narratives, economic drivers are the strongest incentive to shift to EVs. This builds on "greening" the current model of private vehicular use in order to maintain it, as less cars and a shift to other transport modes would affect the automotive industry. Given the infrastructure required for the mass implementation of EVs and the stock of batteries and cars that would need to be produced, pushing for this technological pathway would generate a lock-in for years to come.

Science has a part to play in legitimizing alternative visions of the future. There are many life cycle assessments comparing EVs to ICEVs (see, for example, some of the studies cited in this Chapter). These analyses are valuable and necessary. However, using them as the only input for decision-making assumes that the role of policy is to guide a structural, technological sustainability transition. Functional, behavioural changes can also be pushed by policy, but in order for this to happen, a wider range of studies needs to filter across the science-policy interface (including social science studies – see, for example, Sovacool et al (2018) and Bergman et al (2017)). As stated by Lövbrand (2011, p. 231): "There may be a trade-off between research co-produced to be accountable to the knowledge needs of societal decision-makers, and co-produced research that seeks to challenge and transform existing ways of thinking". Alternative visions of future mobility that challenge dominant behaviours, for example futures centred around car-sharing, public transport and reduced travel distances, can be shaped by research that is produced outside of the current techno-optimist epistemic box. Rather than only asking whether EVs are more or less sustainable than ICEVs, this means asking what a sustainable transport future may look like outside of the private vehicle paradigm.

Chapter 5

Energy systems are multi-scale and complex: Implications for science and for EU policy

In this Chapter, I expand on the hierarchical framework introduced in Chapter 2 in relation to Catalonia's electricity sector, applying it to the full energy sectors of Spain, Sweden and the EU. I include externalised energy processes, building on work which has been developed in collaboration with Maddalena Ripa (Ripa et al., 2021). An open-access nexus database was compiled using different data sources. The database was used to assess the local and externalised inputs and outputs associated with the full energy sectors of Spain, Sweden and the EU, as well as the inputs and outputs associated with lower-level components of the energy sector (the fuel, heat, electricity and gas sectors). This allows viewing the energy sector across three different scales: the micro-scale, at the level of structural processors; the meso-scale, at the level of extensive and contextualised functional processors; the macro-scale, at the level of the energy sector as a whole. Differently from other chapters, the work presented here is unpublished. Part of the results, however, have been included in the MAGIC deliverable 4.4, "Report on the experience of applications of the Nexus Structuring Space in Quantitative Storytelling" (Giampietro et al., 2020). As such, results have an exploratory nature. I focus my discussion around two themes that are central to EU energy policy: decarbonisation and energy security. Decarbonisation narratives underestimate the role played by externalised processes and do not address the vast predominance of fuels as an energy carriers. Energy security narratives use narrow problem definitions, focusing on political concerns which do not adequately address the ties between security and decarbonisation. These topics will be further explored in a publication with Laura Pérez Sánchez, Michele Manfroni and Mario Giampietro.

5.1. Introduction

Researchers and policymakers alike widely agree that energy systems are complex. At the 2019 Conference on Cyber Security in the Energy Sector, the European Commissioner for Climate Action Miguel Arias Cañete opened with: "The energy system is one of the most complex and largest infrastructures in Europe" (EC, 2019c). Interpretations of what is discussed when talking about energy systems, and what is meant when referring to complexity, vary. In a 2015 review paper, Bale et al. (2015) highlight eight characteristics of complex systems that are relevant to energy systems: agents, networks, dynamics, self-organisation, path dependency, emergence, co-evolution, learning & adaptation. These characteristics focus on the evolution and dynamics of complex energy systems. In this view, the system encompasses actors and institutions as well as technology and infrastructure, including material and immaterial networks. Taking an alternative (but not dissonant) perspective, in this Chapter I view energy systems from a biophysical perspective, focusing on their multi-scalarity and on their functions. Functions are related to the final cause of the system, i.e., the concerns and purposes of actors and institutions. Thus, although actors and institutions are not included as material entities in the model, they affect and are affected by the organisation and evolution of the biophysical system. As in the rest of this thesis, I take a definition of complexity that stems from the relationship between system and observer (Rosen, 1958; Allen et al., 2017). I focus on three system-observer interactions which are relevant for the representation of energy systems at the science-policy interface:

- The pre-analytical choice of how to define the system, i.e., what to include and what not to include in the model, in terms of boundaries, variables and scales.
- The different representations of the system across different scales.
- The different representations of the system by different actors.

These three system-observer interactions are shown in Figure 13. In the systems under study (Spain, Sweden and the EU), the pre-analytical choice of what to include in the energy system highlights nexus interactions. Input and output variables include primary energy sources, energy carriers, human activity, land use, water, waste and GHG emissions.

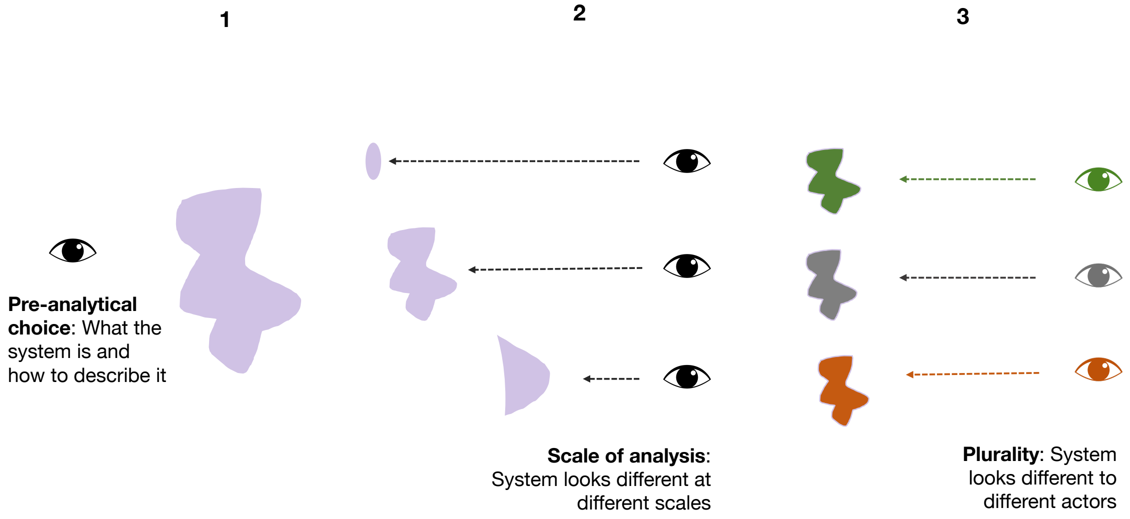

Figure 13. System-observer relationships for complex energy systems

However, the methodology is open to different variables being included (it is semantically open). Representations at different scales are included by formalising three scales and how they are connected to one another. Following Ripa et al. (2021) and Giampietro et al. (2020) I refer to these as the micro-scale, the meso-scale and the macro-scale. The micro-scale describes inputs and outputs of technological (structural) types. The meso-scale aggregates structural descriptions into functional ones, based on end uses (i.e., which energy carrier is being produced by the different structures). At this scale, processors are also contextualised with respect to what is produced locally and what is imported. The macro-scale, then, describes the behaviour of the energy sector as a whole, highlighting the interactions with other societal compartments (its role in the metabolism of the social-ecological system). The third system-observer interaction is about the existence of a plurality of legitimate views. The interpretation of results presented here takes a critical perspective, based on my own placing within the MAGIC project, where the aim has been to generate uncomfortable knowledge (Rayner, 2012). I use the quantitative results to discuss the quality of narratives underpinning two topics that are central to EU energy policy: decarbonisation and energy security. A discussion of these same results with different stakeholders would generate different perspectives, which would be fruitful and necessary if models such as these were used to inform decision-making processes.

In Chapter 2, I introduced a hierarchical organisation of Catalonia's local electricity sector, focusing on the distinction between functional and structural elements. Here, I expand on that in three ways: (i) including the provision of heat, fuel and gas energy carriers, in addition to electricity; (ii) describing the energy systems of Spain, Sweden and the EU as a whole; (iii) including processes that take place outside of the boundaries of each system (externalised processes). Instead of focusing on the evolution of energy systems through time, I take a static snapshot of the three systems (Spain, Sweden and the EU) for the year 2018, and inspect multi-scalarity in terms of organisation, spatial scales and dimensions. In particular, I include multiple nexus dimensions, using the tool of the metabolic processor; multiple spatial scales (national with Spain and Sweden, supra-national with the EU); and multiple hierarchical levels.

Information at different scales is relevant to inform different aspects of the energy system, which is why relying on single indicators or targets, such as "efficiency", may not generate the desired policy outcomes (efficiency at the technological level, e.g., a coal power plant producing more electricity with less coal, is different from efficiency at the functional level, e.g., the energy sector producing more fuels with less electricity) (Dunlop, 2019; Velasco-Fernández et al., 2020). Since scientists are situated within the system-observer relationships, guiding decision-making through formal models becomes part of governance *in* complexity, rather than of governance *of* complexity. In this spirit, the model presented is open and exploratory, and all data and codes are freely available for others to use. The rest of this Chapter presents an overview of the work in progress and starts addressing some of the questions which can be approached through the methodology. Section 5.2. summarizes the methods used to generate quantitative results, focusing on the collection and aggregation of data across different scales. Results follow. I show the functional holarchies of the energy systems of Spain, Sweden and the EU. Local and externalised processes are included in the holarchies. Sample results on local and externalised GHG emissions, human activity and use of primary energy sources are shown for each country and each energy carrier. Section 5.4. discusses these results in relation to decarbonisation and energy security.

5.2. Data & Methodology

The generation of quantitative results followed a bottom-up approach, in four steps (Figure 14). First, inputs and outputs for different energy processes were collected. Following Chapter 2, we refer to these energy processes as structural types, differently from structural instances which may be specific power plants or mines, and from functional types which are aggregations of structural types based on their functionality within the energy sector. Given the lack of a standardized database including nexus variables associated with structural types, different data sources were used, including the Ecoinvent database, data from Eurostat and the NREL U.S. Life Cycle Inventory Database. Table 10 shows the structural types included in the database, organized by type of process. Table 11 lists the inputs and outputs that were collected for each type. Similar to Chapter 2, in the three case studies we do not consider transport of primary energy sources, and transmission and distribution of energy carriers. The database includes details on which data are system-specific and which ones are benchmarks. Details on the assumptions made in compiling the nexus database are included in the Appendix A3.1.

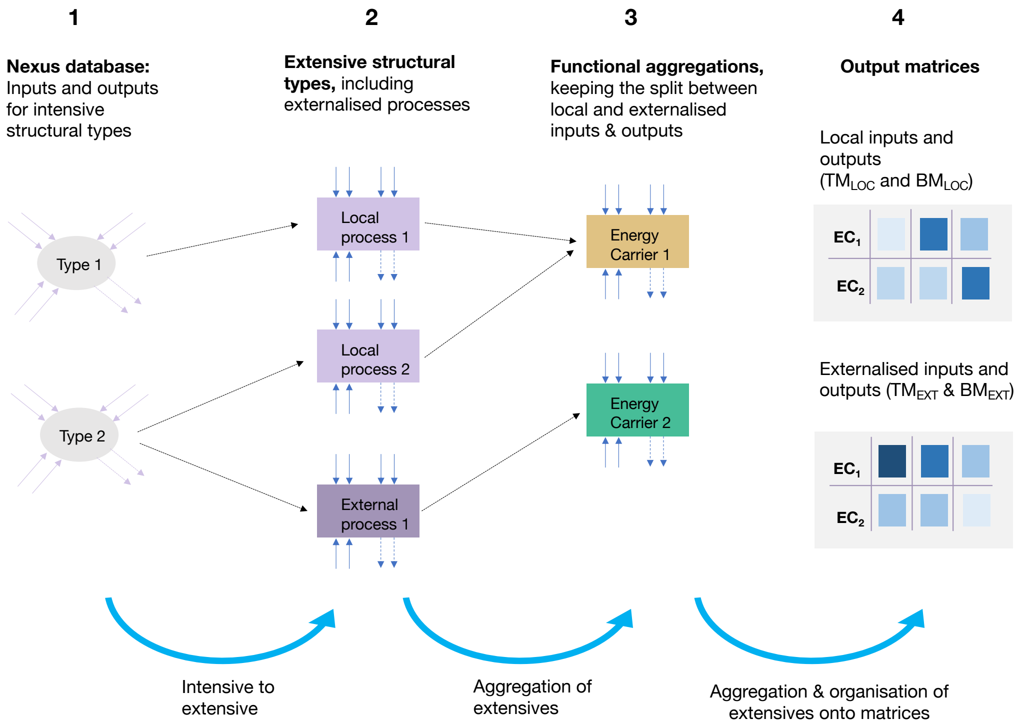

Figure 14. Schematisation of methodological steps. EC_1 is Energy Carrier 1, EC_2 is Energy Carrier 2, TM_{LOC} is the Local Technosphere Matrix, BM_{LOC} is the Local Biosphere Matrix, TM_{EXT} is the Externalised Technosphere Matrix, BM_{EXT} is Externalised Biosphere Matrix

Table 10. Structural types

Name	Category	Name	Category
In situ leaching uranium mining	Mining & Extraction	CHP Spain	Combined Heat & Power (CHP)
Open pit uranium mining	Mining & Extraction	Biomass CHP plant Sweden	Combined Heat & Power (CHP)
Underground uranium mining	Mining & Extraction	Waste CHP plant Sweden	Combined Heat & Power (CHP)
Underground coal mining	Mining & Extraction	Other CHP Sweden	Combined Heat & Power (CHP)
Open pit coal mining	Mining & Extraction	Other CHP plants EU	Combined Heat & Power (CHP)
Lignite mining	Mining & Extraction	Coal CHP plant EU	Combined Heat & Power (CHP)
Onshore light oil extraction	Mining & Extraction	Natural gas CHP plant EU	Combined Heat & Power (CHP)
Offshore light oil extraction	Mining & Extraction	Lignite CHP plant EU	Combined Heat & Power (CHP)
Onshore medium oil extraction	Mining & Extraction	Biomass CHP plant EU	Combined Heat & Power (CHP)
Offshore medium oil extraction	Mining & Extraction	Waste CHP plant EU	Combined Heat & Power (CHP)
Onshore heavy oil extraction	Mining & Extraction	Natural gas turbines	Power plant
Offshore heavy oil extraction	Mining & Extraction	Solar PV	Power plant
Onshore gas extraction	Mining & Extraction	Wind turbines	Power plant
Offshore gas extraction	Mining & Extraction	Hydro	Power plant
Nuclear fuel element plant	Intermediate PES conversion	Pumped hydro storage	Power plant
Coke oven	Intermediate PES conversion	Nuclear plant	Power plant
Biomass heat boiler/furnace	Derived heat plant	Coal power plant	Power plant
Waste heat boiler/furnace	Derived heat plant	Petroleum products plant	Power plant
Heat pump	Derived heat plant	Other electricity Spain	Power plant
Other heat boilers/furnaces Sweden	Derived heat plant	Lignite power plant	Power plant
Natural gas heat boiler/furnace	Derived heat plant	Other electricity EU	Power plant
Coal heat boiler/furnace	Derived heat plant		
Other heat boilers/furnaces EU	Derived heat plant		
Biodiesel refinery	Refinery		
Bioethanol refinery	Refinery		
Hydroskimming refinery	Refinery		
Medium conversion refinery	Refinery		
Deep conversion w/ coking refinery	Refinery		
Deep conversion w/ hydrocracking refinery	Refinery		

Table 11. Nexus inputs and outputs associated with each structural type

Orientation	Name	Unit	Orientation	Name	Unit
input	land use	ha	output	greenhouse gases	kg CO_2 eq.
input	human activity	hrs	output	water (natural bodies)	l
input	water (natural bodies)	l	output	spent nuclear fuel	kg
input	water (from tap)	l	output	coal	kg
input	power capacity	MW	output	uranium	kg
input	coal	kg	output	lignite	kg
input	uranium	kg	output	gas	m^3
input	lignite	kg	output	oil	kg
input	gas	m^3	output	biomass	kg
input	oil	kg	output	waste	kg
input	biomass	kg	output	coal products	kg
input	waste	kg	output	manufactured gas	MJ
input	coal products	kg	output	other solid fossil fuels	kg
input	manufactured gas	MJ	output	other hydrocarbons	kg
input	other solid fossil fuels	kg	output	nuclear fuel element	kg
input	other hydrocarbons	kg	output	total oil products	MJ
input	nuclear fuel element	kg	output	electricity	MJ
input	oil products	MJ	output	derived heat	MJ
input	electricity	MJ	output	biofuels	MJ
input	derived heat	MJ	output	biogas	MJ
input	biofuels	MJ			
input	biogas	MJ			

Each input and output of the database is expressed per unit of primary energy source or energy carrier output. For example, inputs and outputs of the "lignite power plant" type are scaled by 1 MJ of electricity output, while inputs and outputs of the "offshore gas extraction" type are scaled by 1 m^3 of natural gas. For CHP, the main output is determined in context: "CHP Spain" is scaled by MJ of electricity, as all CHP in EU, since electricity is the primary output of these processes. In Sweden, since CHP plants produce more derived heat than electricity, CHP types are aggregated under "heat" rather than "electricity", meaning that the structural types of Swedish CHP are scaled by 1 MJ of derived heat. Once the nexus database was compiled (at the microscale), the second step consisted in scaling each intensive structural type onto contextualised, extensive representations (mirroring the workflow of Chapter 2). This required two types of information:

- Data on extensive outputs of each local process, e.g., how much lignite is mined in the EU and how much is imported. Most of these outputs were available from Eurostat, although some structural distinctions required data from other sources (e.g., how much gas is extracted onshore vs. offshore).
- Data on externalised process, including: (i) the extensive output of each externalised process; (ii) the origin of each externalised process, to determine the structural mix (e.g., how much of the gas imported within the EU is extracted offshore vs. how much is extracted onshore).

Following the analysis presented in Ripa et al. (2021), externalised primary energy sources are the sum of the primary energy sources imported directly (such as imported oil) and of the primary energy sources imported indirectly, i.e., those needed to produce energy carriers that are imported directly (such as the oil needed to produce imported fuels). This total externalised quantity is then associated with a set of inputs and outputs (often referred to in the literature as "virtual" or "embedded" imports -- for example, the water needed to mine imported coal, and to mine the coal embedded in electricity imports). Since externalisation can be calculated recursively and indefinitely, system boundaries are needed. Those boundaries are set at the extraction of primary energy sources needed to produce imported energy carriers. This means that the electricity needed to extract the oil used to produce imported fuels is accounted for, but we do not account for the inputs and outputs associated with the production of that electricity. The way externalised primary energy sources PES_{EXT}, externalised energy carriers EC_{EXT} and externalised nexus inputs and outputs $(In/Out)_{EXT}$ are calculated with respect to these system boundaries is shown in Equations 1-3. Similar to the first step, assumptions and data sources for this second step are included in the Appendix (A3.1.4).

$$PES_{EXT} = PES_{DIR} + PES(EC_{DIR}) \tag{1}$$

$$EC_{EXT} = EC_{DIR} + EC(PES_{EXT}) \tag{2}$$

$$(In/Out)_{EXT} = In/Out(PES_{EXT}) + In/Out(EC_{DIR}) \tag{3}$$

Equations 1-3. PES_{EXT}, EC_{EXT} and $(In/Out)_{EXT}$ are externalised PES, EC, and nexus inputs & outputs (such as water, GHG, etc.); PES_{DIR} and EC_{DIR} are direct imports of PES and EC; $PES(EC_{DIR})$ are the PES needed to produce $EC_{DIR;}$ $EC(PES_{EXT})$ are the EC needed to extract PES_{EXT}; $In/Out(PES_{EXT})$ are the nexus inputs & outputs associated with PES_{EXT}; $In/Out(EC_{DIR})$ are the nexus inputs/outputs associated with EC_{DIR}

The third step consisted in aggregating extensive structural types (i.e., those characterising the actual size of flows), based on their functionality. Functional types were expressed based on which energy carrier was being produced: electricity, derived heat, gas or fuels (including both oil products and biofuels). The energy carrier gas refers only to the gas consumed directly as an energy carrier (i.e., the gas consumed by sectors such as households and services) and not to natural gas used as a primary energy source (e.g., the gas used to produce electricity). In this third step, the disaggregation between local and externalised inputs and outputs is maintained. In the fourth and final step, extensive inputs and outputs associated with functional types are mapped onto four matrices, describing the energy sector as a whole:

- Local Technosphere Matrix (TM_{LOC}): local inputs and outputs to and from the technosphere.
- Externalised Technosphere Matrix (TM_{EXT}): externalised inputs and outputs to and from the technosphere (i.e., outside the geographic boundary of the analysed system).
- Local Biosphere Matrix (BM_{LOC}): local inputs and outputs to and from the biosphere.
- Externalised Biosphere Matrix (BM_{EXT}): external inputs and outputs to and from the biosphere (i.e., outside the geographic boundary of the analysed system).

The collection of nexus inputs/outputs in step 3 also results in these matrices for each sub-sector (electricity, derived heat, fuels and gas). This view at different scales (energy sector as a whole vs. each sub-compartment) helps in understanding how trends at the level of the energy sector emerge (e.g., which energy carrier leads to the most externalised GHG emissions). The nexus database, as well as the scaling relationships for the three systems under study (Spain, Sweden and the EU), are available through Zenodo[16] (Di Felice, 2020).

5.3. Results

5.3.1. Holarchies of energy processes

Figures 15, 16 and 17 show the holarchies of energy processes in Spain, Sweden and the EU, moving from the micro-scale of structural processors to the macro-scale of the energy sector. In the lower part of each figure, the relevant structural processors for the energy metabolism of each case study are shown. To simplify the representation, only those processes contributing to a minimum of 5% within their category are included. The colour of the nodes at this level represents whether a process is local or externalised (grey for externalised and blue for local). The size of each processor reflects its relative size *within its category,* since processes cannot be compared across categories (a tonne of oil cannot be compared to a MJ of electricity). Each of these nodes is associated with a set of nexus inputs and outputs (not shown in the Figures). Seven broad categories are included: oil, gas, coal & lignite, uranium (PES extraction); power plants, refineries and heat plants (PES conversions). The former category reflects the interactions of the energy system with PES found in the biosphere, while the latter (on the bottom right of the Figure) reflect processes in the technosphere, under human control.

While these processors connect to one another through sequential pathways, those pathways are broken down here, focusing on a hierarchical mapping rather than a sequential one (which is why we refer to these as holarchies). Moving to the meso-scale, each node is mapped onto a functional category. Some nodes are split across multiple categories (for example, oil in Spain is used both for fuels and for electricity). In practice, the processor was split into two components (oil for fuels and oil for electricity).

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[16] Since the database has yet to be peer-reviewed, it is shared now for reviewing purposes. It will be freely available and open to the public once it has undergone peer review

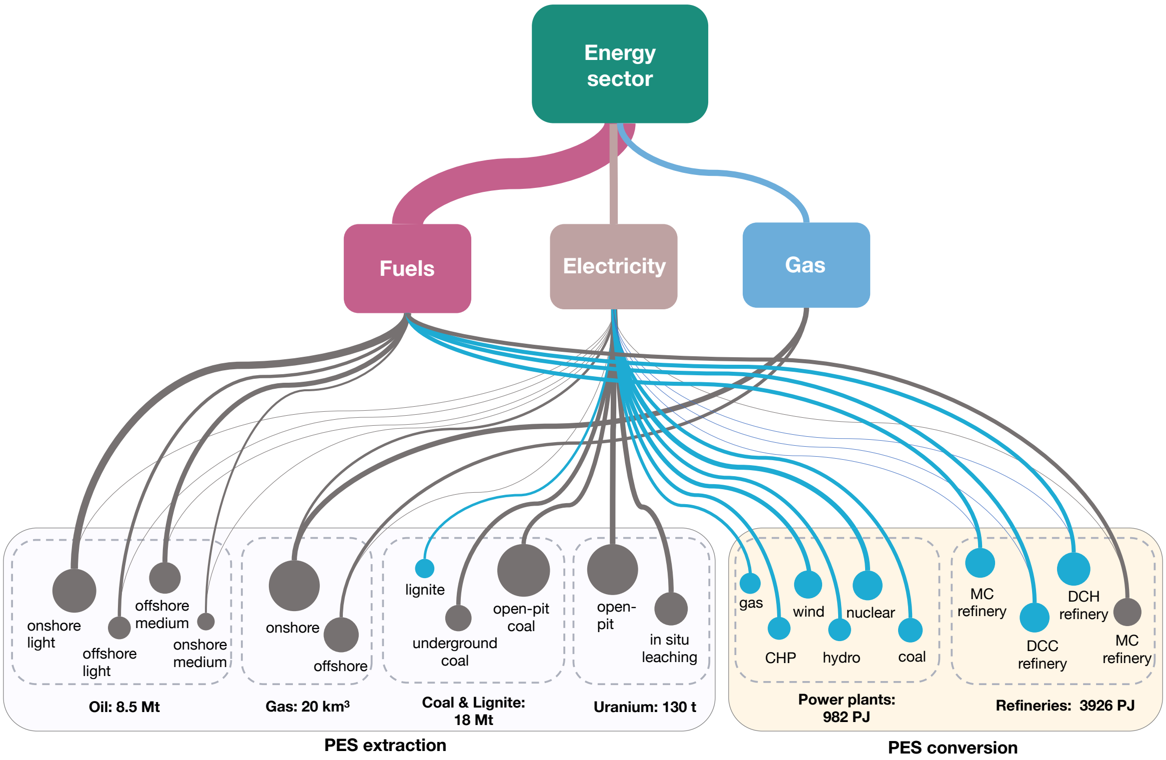

Figure 15. Holarchy of energy processes for Spain, 2018. light: light oil; medium: medium oil; MC: medium conversion; DCC: deep conversion with coking; DCH: deep conversion with hydrocracking

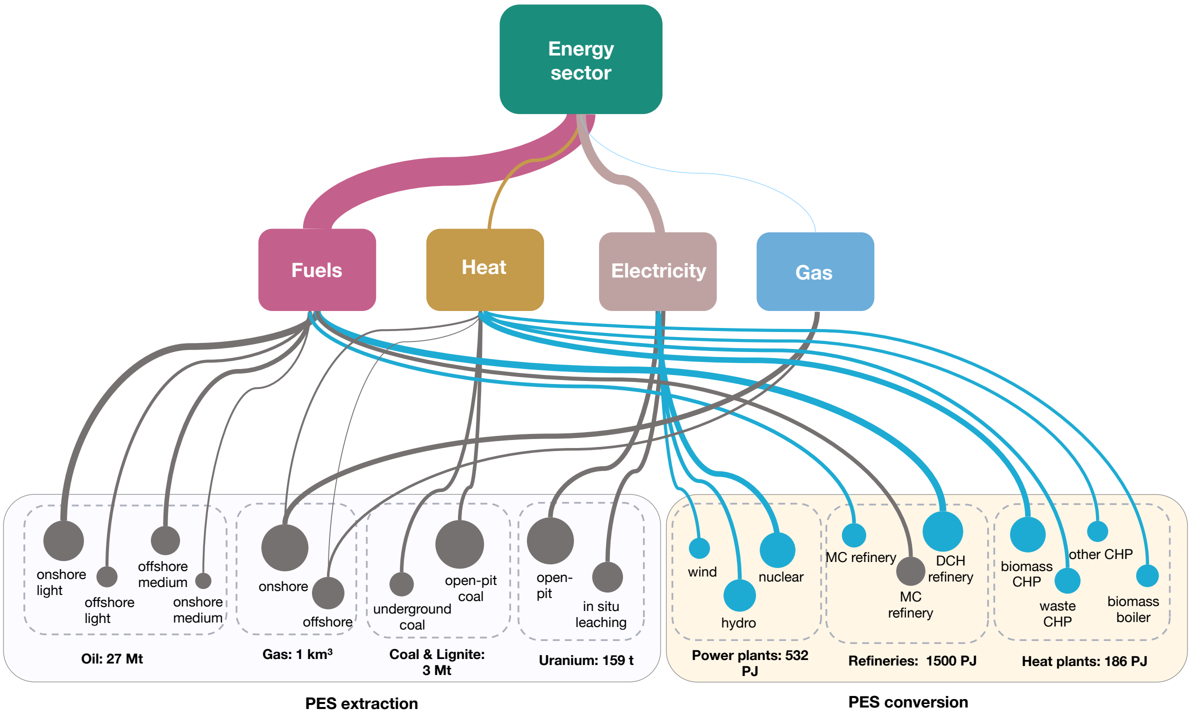

Figure 16. Holarchy of energy processes for Sweden, 2018

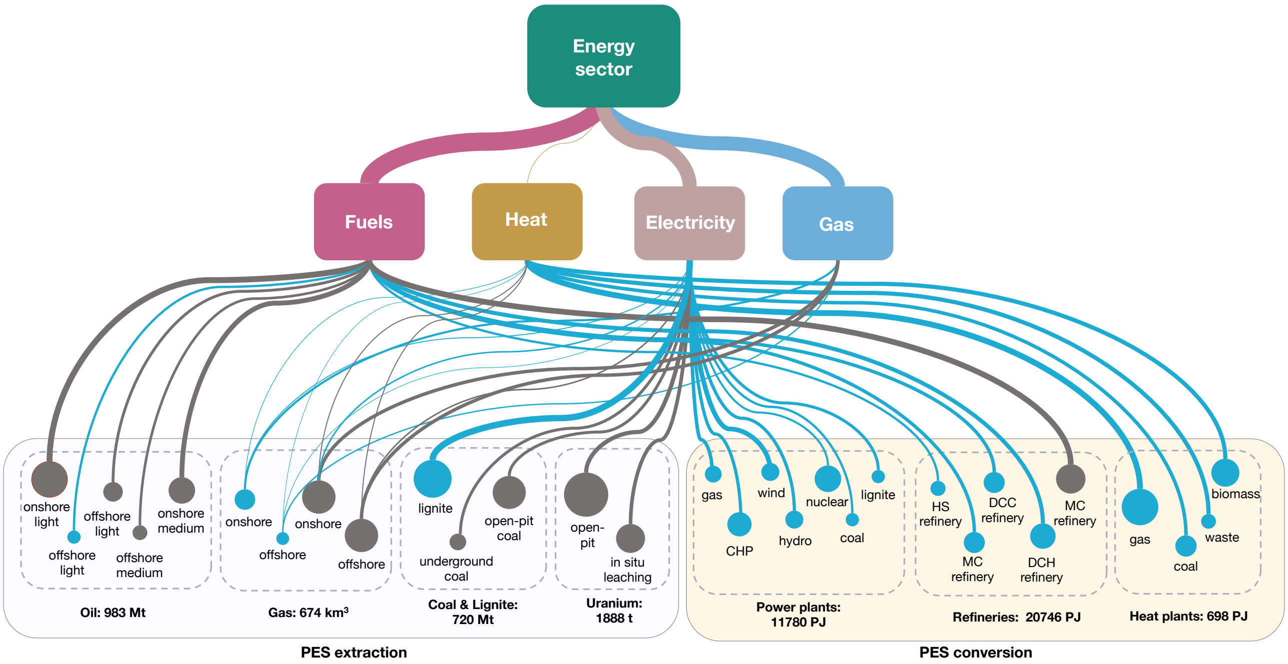

Figure 17. Holarchy of energy processes for the EU, 2018

The relative size of the flow aggregating from the micro-scale to the macro-scale reflects how much of the extensive output of that processor contributes to each functional compartment (most of the oil in Spain is for fuel production for final consumption, with a small part is allocated to fuels which are then used in petroleum product plants). The mapping from the meso-scale to the macro-scale shows the relative contribution of each energy carrier (fuels, electricity, gas or heat) to the full mix of energy carriers produced by the energy sector. To allow for this comparison, the final consumption of each energy carriers is expressed in the same unit of joules, taking the data directly from Eurostat, thus following their conversion assumptions between types of carriers. These holarchies, mirroring Figure 6 in Chapter 2, provide a first glance into the main characteristics of the energy sector of each case study, by looking at the mappings between structure and function. In each case, PES extraction is almost entirely externalised, with the exception of some lignite extraction in Spain and some lignite, gas and oil extraction in the EU. The biomass needed for heat plants in Sweden is not included, as data on transformation inputs of biomass are missing from Eurostat[17].

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[17] The methodology does allow for this to be included, if one wanted to study, for example, the heat sector in Sweden

PES conversion, on the other hand, is mostly local, with the exception of some fuel imports[18]. While renewables play an important role in the electricity generation for each case study, refineries are almost entirely fossil-fuelled (biorefineries account for less than 5% of total fuel consumption). Heat is also generated mostly with gas and coal in the EU, while biomass and waste play an important role in heat generation in Sweden. Moving up from the meso-scale to the macro-scale, the relative importance of each energy carrier is shown. This is a necessary simplification, since different energy carriers play different roles in society and they are not all interchangeable. Despite these limitations, a comparison across energy carriers shows how fuels play a central role in the energy metabolism of each case study, although differences arise among them: Sweden, for example, has an almost negligible consumption of gas as an energy carrier, while there is no derived heat production in Spain. Differences and similarities across case studies can be further inspected by looking at the nexus patterns associated across compartments of the energy sector.

5.3.2. Output matrices

The full technosphere and biosphere matrices (local and externalised) for each functional compartment (electricity, heat, fuel and gas) and for the energy sector as a whole, for the three case studies, are included in the Appendix (A3.2., Table 17 for Spain, Table 18 for Sweden and Table 19 for the EU). A selection of these results is shown in Figure 18. The left side of the Figure shows hours of human activity invested per capita, per country and per sector. The right side shows the same for GHG emissions. Per capita results allow comparing across countries, while extensive results may be useful for other purposes, such as informing local policies. In terms of human activity, both local and externalised processes have a low investment of hours per capita in the energy sector, reflecting the sector's high metabolic rate due to its tecno-capitalisation (i.e., high investments of exosomatic energy and low investments of endosomatic energy). On average, the EU externalises more human activity per capita as it employs locally, despite the local production of energy carriers.[19]

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[18] This is also a consequence of our assumptions: for simplicity, we assumed electricity imports to be negligible in each case, as they contributed to less than 5% of total electricity consumption.

[19] Including transport, transmission and distribution would increase the amount of local employment

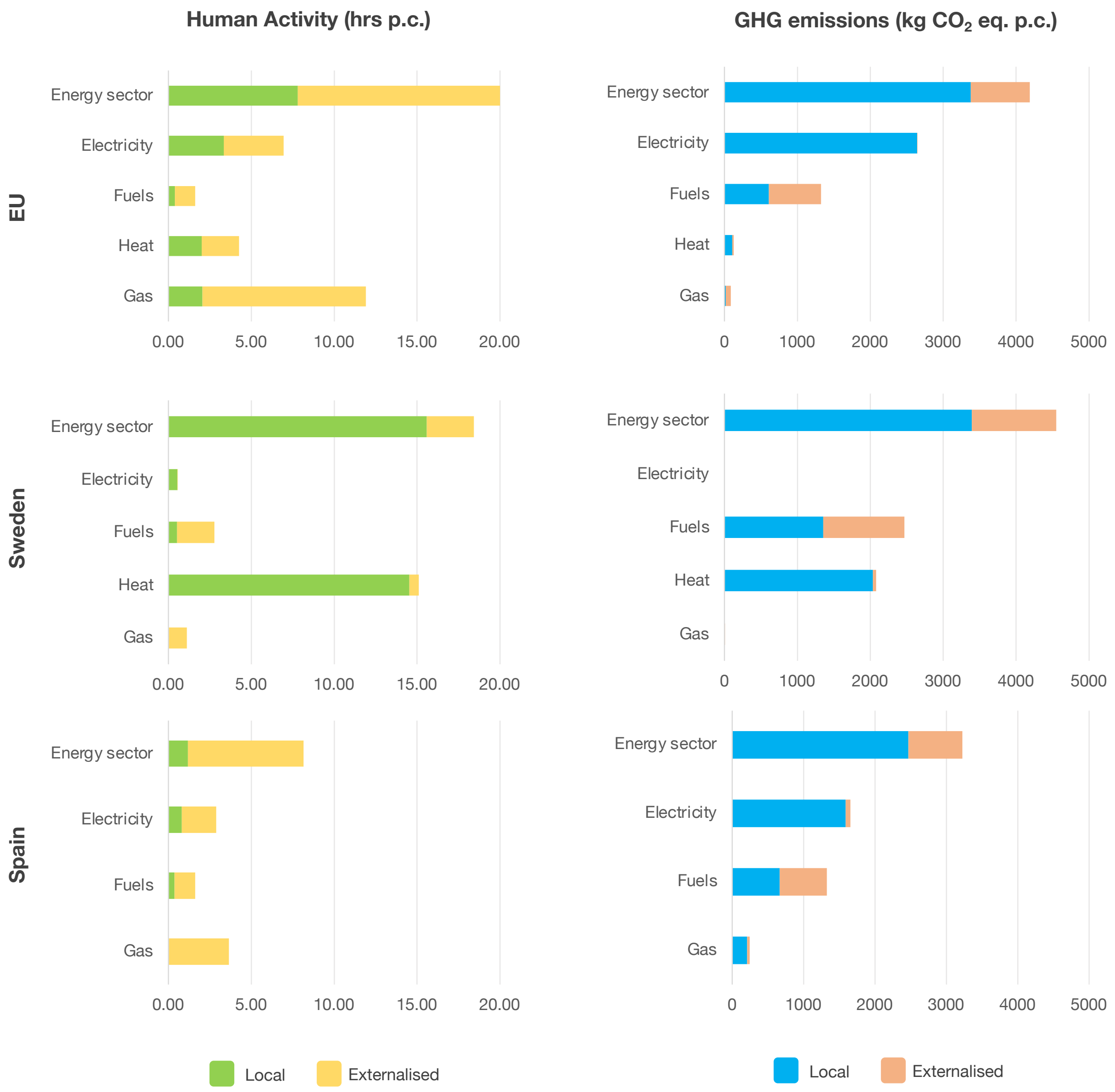

Figure 18. Local and externalised human activity and GHG emissions per capita, per energy sector and per case study, for the year 2018

Electricity production tends to be the segment of the energy sector with highest GHG emissions. These are negligible for Sweden, however, since it produced electricity with nuclear power, hydropower and wind turbines (while these processes do not have zero emissions, their operational emissions are negligible when compared with other segments of the energy sector). Despite negligible GHG emissions for electricity production, average GHG emissions per capita in Sweden are higher than for Spain and slightly higher than the EU average. This is due to high consumption of fuels and heat paired with a low population. The "fuels" segment only accounts for the emissions associated with fuel production (oil extraction, refineries and biorefineries), and not for the emissions of those fuels being burned in other sectors (such as transport). Focusing on primary energy sources, Figure 19 shows local and externalised production of coal, oil and uranium (in kg per capita for coal and oil, and grams per capita for uranium).

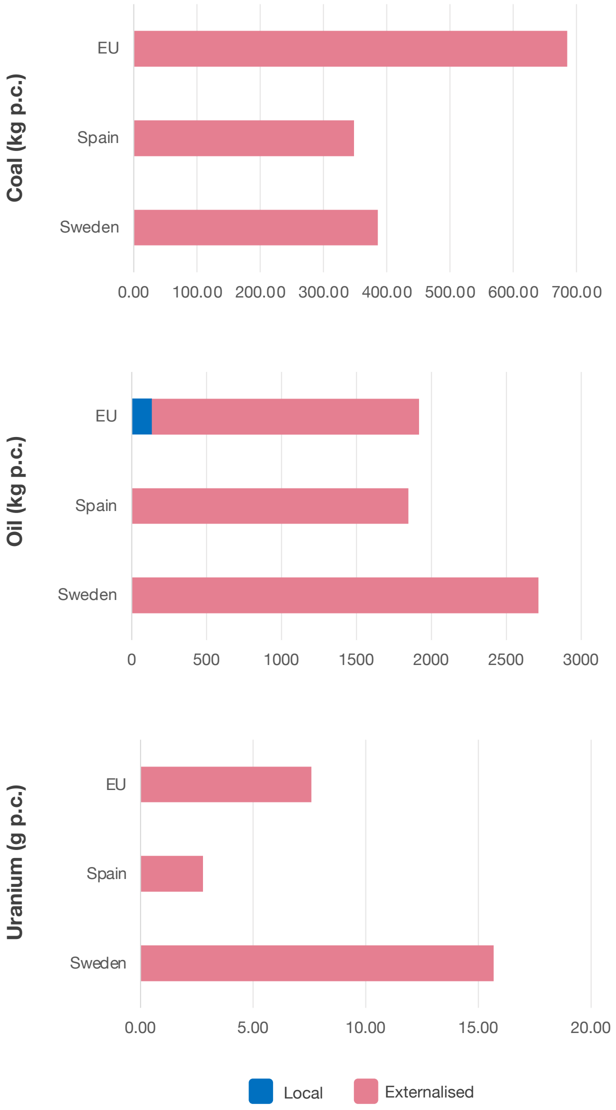

Figure 19. Local and externalised production of coal, oil and uranium (in kg per capita) for EU, Spain and Sweden, 2018.

5.4. Discussion

5.4.1. Decarbonisation

EU decarbonisation narratives are centred on the coupled concerns of climate change, energy security and economic growth. Decarbonising the economy is seen as a way to tackle these concerns simultaneously. Within the energy sector, this action is to be implemented through the mechanism of increasing the share of renewables in the energy mix. In practice, the EU plans to be carbon-neutral by 2050, in line with the European Green Deal and with the Paris Agreement (EC, 2020c). The energy sector accounts for approximately 30% of total GHG emissions in the EU[20] (Eurostat, 2020c). This excludes the emissions from fuels produced in the energy sector and consumed by other societal compartments, adding up to almost 50% of total GHG emissions (of which almost half is for transport) (Eurostat, 2020c). The Recast Renewable Energy Directive set a binding target for 32% of EU's energy sources to be renewable by 2030. The directive also specified national renewable energy targets for 2020, with countries developing their own renewable trajectories through national plans. The national plan for Spain set a renewable target of 22.7% by 2020, while Sweden's ambitious plan aimed for a 50% target by the same year (EC, 2020d). According to Eurostat, Sweden did reach this goal, together with ten other EU countries, while Spain failed (Eurostat, 2020d). Looking at the holarchies of Figures 15-17 allows us to critically inspect these targets and trajectories.

Firstly, the way primary energy sources are extracted and converted into energy carriers with different functions can accommodate different types of comparative calculations among types of energy sources. A kilogram of coal cannot be compared with a kilogram of uranium. What is compared by Eurostat is the percentage of renewable sources in final energy consumption. This requires converting primary energy sources from physical quantities (e.g., kilograms) to energy ones (such as MJ), and this conversion builds on underlying assumptions, mixing types of energy and scales (Giampietro and Sorman, 2012). Adding to this, our analysis shows how different types of primary energy sources are associated with different local and externalised nexus patterns. While Sweden's local

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[20] This is listed as "energy industries" in Eurostat, i.e. "emissions from fuel combustion and to a certain extent fugitive emissions from energy industries, for example in public electricity, heat production and petroleum refining" (Eurostat, 2020c)

electricity is produced by a high share of renewables, the other primary energy sources used by the country are entirely imported. As a consequence, GHG emissions of the fuel sector, for example, almost double when externalised processes are taken into account.

Secondly, the meso-scale shows how different primary energy sources and converters of energy carriers are mapped onto functions of the energy system. From this, it is clear how Sweden's renewable share is high in the electricity mix and in the heating sector (if biomass and waste are considered as renewables), but negligible in the fuels sector. Achieving the 50% target of renewable share (according to Eurostat calculations) does not imply that this trend will continue in the future, unless consumption of different energy carriers also shifts. In simple terms, Sweden has reached its renewable target by focusing on the low-hanging fruit of electricity generation, while decarbonising the fuels sector is a whole different beast. Even within the electricity sector, a high renewable penetration does not indicate that a fully renewable electricity mix is easily achievable. The generation of baseload electricity through nuclear power allows for intermittents to cover the rest of the electricity curve. Replacing nuclear power would require some form of storage, posing biophysical and socio-economic challenges (see the discussion on lithium and storage for EVs in Chapter 4, and Renner and Giampietro (2020) for further details on the challenges of decarbonising electricity).

Taking an alternative view to EU targets (missed and achieved), Figure 18 shows how Spain has lower GHG emissions per capita than Sweden, despite Sweden's higher renewable electricity mix. This is due to (i) Sweden's lower population and (ii) Sweden's high GHG emissions in the heating sector, due to the colder climate. Looking at the structural mixes, some gas and coal are used in Sweden's heating sector. In addition, GHG emissions of biomass and waste heat plants are far from zero: according to our data, biomass and waste CHP plants and boilers alone account for over half of Sweden's local GHG emission mix. Externalised GHG emissions are also non-negligible for both countries, highlighting the need for decarbonisation policies which take into account the openness of the system (by setting limits on fossil fuel imports, for example). The difference in the energy metabolism of the two countries and the per capita view of environmental impacts suggest that the flat targets set by EU energy policies may not be suitable in achieving a carbon-neutral economy. While Sweden has reached its renewable energy target, if everyone in the EU consumed the same pattern of energy products as Sweden, global (local plus externalised) GHG emissions would increase.

5.4.2. Energy security

Energy security is associated with multiple non-reducible dimensions, as discussed in Chapter 3. A predominant tone of energy security discourses in EU policy is the military one. Imports in general are not the issue. Rather, problems arise from the reliance on imports from a few "politically unstable" regions (EC, 2013). This became clear following the gas and oil disputes between Russia, Ukraine and Belarus (Vahtra, 2009), leading to a securitization of energy policy priorities in the EU context. Sweden and Spain import almost all of their primary energy sources, while the EU has some mining and extraction. These are minor compared with direct and indirect imports, as can be clearly seen for the examples of oil, coal and uranium in Figure 19.

A heavy reliance on imports is framed as negative by EU energy policy. This predominant energy security narrative, that producing locally is better than importing, is contested when viewed from a metabolic perspective. Looking at local and externalised nexus patterns associated with energy imports shows how a reliance on externalised processes also leads to the externalisation of inputs and outputs, both in the technosphere and in the biosphere. Viewing the EU's energy sector as a whole, externalised processes account for approximately 20% of GHG emissions and 20% of water consumption (not accounting for flows of water abstracted and then released back to natural bodies)[21]. Importing energy products also means that the requirement of human activity in paid work is externalised, although labour investments in extraction and mining tend to be low in labour inputs and high in energy ones. Connecting this to the question of decarbonisation, a shift to a decarbonised energy system while maintaining current consumption patterns would require some combination of grid-level storage, storage in electric vehicles, alternative fuels and reliance of biomass. These may require, in turn, an additional boost to material imports (see the discussion on lithium in the previous Chapter), trade-offs with food security or trade-offs with security of supply for consumers. The tension between system openness and environmental impacts seems central to the future evolution of the EU energy system, reflecting deeper tensions between high-level justification narratives. These considerations, however, are out of scope when framed within the set of dominant energy security narratives. These dominant narratives focus on narrow problem definitions (e.g., "importing oil is bad"). Within these narrow spaces, causality can be easily discerned,

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[21] 20% refers to our "water_techno" variable. See Appendix A3.1.1. for details on water accounting

and courses of actions can be decided upon. Our metabolic perspective, however, suggests that political narratives of energy security should be paired with biophysical narratives in order to fit security goals within the EU's wider sustainability agenda.

5.4.3. Conclusions

This Chapter has presented work in progress describing the full energy sectors of Spain, Sweden and the EU across hierarchical levels, in terms of nexus patterns at each level and relations among them. This multi-scalar perspective is grounded in complexity, building on the notion that complex systems cannot be viewed at a single scale of analysis. Building on hierarchy theory, we proposed a minimum of three levels needed to describe the energy system in a way that may be more informative to policy. We do not claim for this representation to be true, but simply for it to be useful in understanding the connections between biosphere and technosphere variables at different scales. The inclusion of a functional meso-scale is particularly important when discussing decarbonisation and energy security, as it shows the renewable contribution to each functional compartment, as well as highlighting the implications of the openness of the energy sector.

In terms of data, a global sensitivity analysis would be useful in improving the robustness of the quantitative assessments (Saltelli et al., 2008). Given the variety of data sources and assumptions used throughout the analysis, this is not a trivial task, and how it will be carried out also depends on the purpose of the numbers themselves, as highly precise number may generate a false sense of certainty when discussing processes beyond the technological level. The usefulness of the approach lies the reconstruction of macro-scale behaviours from micro-scale ones, collecting and aggregating bottom-up data. The information included in the nexus database and in the aggregations across levels is rich, and a small portion of this information was showed here for illustrative purposes. Future work will tighten the connections between the quantitative assessment and narratives in EU energy policies, providing alternative narratives to the dominant ones of decarbonisation and energy security.

Chapter 6

Conclusions

This thesis has inspected energy systems at the science-policy interface through the lens of relational complexity. I have presented four case studies relevant to EU energy policy, addressing different geographical scales (local, national and supra-national) and different themes, including energy security, decarbonisation, externalisation and sustainable transport. Narratives, intended as constructions necessary to infer causal relationships across impredicative events, have been a unifying thread across the four case studies. This thread was advanced in the discussion of science-policy relations with respect to energy security (Chapter 3) and electric vehicles (Chapter 4), and in the development of multi-scale models of energy systems (Chapters 2 and 5). I ended Chapter 1 with three interlocking research questions. I now address these questions in light of the case studies, pointing to answers as well as limitations and emerging reflections.

My first research question asked how perceptions of social-ecological systems can be modelled across levels and dimensions. There are many valid answers to this. I have focused on the perspective of hierarchy theory, presenting a multi-scalar modelling approach, where scale is used to also encompass the hierarchical levels of analysis of energy transformations. The methodological advancements, focused on modelling energy systems with respect to patterns of nexus inputs and outputs, were presented in Chapters 2 and 5. The main contributions have been the introduction and development of metabolic processors as tools for nexus analysis; the functional aggregation of structural elements in a meso-scale description; the acknowledgment that a minimum of three levels of analysis is necessary to describe energy systems in a way that may inform sustainability policies. These developments have by no means been an individual endeavour, but rather a collective trajectory of my research group. In addition, while the exploration of anticipation has not been included in this thesis, metabolic processors, as well as functional aggregations, have been used by others to explore future-oriented questions (see, for example, Renner and Giampietro (2020) and Renner et al. (2020) for food systems).

My second research question shifted from the production of scientific models to the relationship between scientific models and decision-making. I asked what the current relationship between scientific knowledge and sustainability policy looks like, when inspected through the lens of complexity. I did not tackle this question as a standalone investigation, but through chosen examples. Chapter 3 focused on the case of energy security in EU policy. I conceptualised ambiguity as an endogenous feature of relational complexity, serving a purpose for decision-making. I cast doubt on the usefulness of scientific advice attempting to clarify and define the concept of energy security through formal categories, fixed dimensions and indicators. This is a case where science could benefit from acknowledging the political layers of that which it tries to measure. While the academic literature focuses on defining energy security, viewing ambiguity as an issue to be solved, the term's very ambiguity allows for it to be used widely as a policy justification. This resonates with Merton's analysis of the role of functional ambiguity in policymaking and with the concepts of clumsy solutions (Verweij et al., 2006), constructive ambiguity (Berridge and James, 2003) and incompletely theorized agreements (Sunstein, 1995). I added to this existing conceptual landscape by theorising ambiguity in the context of Rosennian complexity.

Chapter 4, on electric vehicles, addressed science-policy relations within this context. I introduced a three-level narrative taxonomy, mirroring the three levels necessary to describe a system in hierarchy theory. I applied this narrative taxonomy, making the distinction between justification, normative and explanation narratives, to analyse EU policy documents related to electric vehicles. I showed how the *normative-justification* relationship, in light of existing research, is uncertain at best. This casts doubts on electric vehicles' potential to simultaneously boost the economy, reduce GHG emissions, improve citizens' wellbeing and increase security. In terms of the science-policy relationship, I argued that scientific assessments run the risk of being generated within the same epistemic boxes as policy solutions, thus implicitly adopting the same set of justifications. I suggested that the generation of scientific knowledge informing policymaking should explicitly address which justifications it builds on. Science built on alternative narratives may be necessary in diversifying science-policy relations, avoiding positive feedbacks and lock-ins. This brings us to my final research question, which is also the most ambitious.

I asked what the role of alternative narratives, and of models built on relational complexity, may be in shifting the science-policy relation. This is a reflexive question, as in practice I am asking if and how my results fit within the existing ecosystem of science for policy. Having thought about these topics for the duration of my Ph.D., I do not have a simple answer to this question. Instead, I have equipped myself with a set of ever-changing beliefs. These beliefs are the result of the research presented in this thesis as much as they are the result of broader collaborations and conversations. Plurality is the theme which I return to consistently when thinking about science-policy relations. Jasanoff (2007) argues that certainty is a myth, and that policymakers should make ethical decisions despite the uncertainty, indeterminacy and ambiguity embedded in the available knowledge base on existing problems. Accepting uncertainty, rather than fighting against it, requires accepting that the integration of plural, often contrasting perspectives is necessary in framing what the issues are, and what desired courses of actions should be taken. Plurality is not a panacea to governance in uncertainty, and any chosen path simplifies reality in a way that generates winners and losers. However, given that we do not know exactly how things work and how they will evolve, it seems that taking a broad view which includes multiple perspectives and models is safer than assuming that it is possible to rely on a single uncontested vision. In practice, in relation to my results, I view the multi-scale nexus perspective of the models presented in this thesis as one of the many angles needed to inform decision-making with respect to sustainability problems. By relating different scales, these models may be useful in framing issues from a systems perspective, while different information may be produced by alternative types of models at each scale. The results presented in the chapters on energy security and electric vehicles, on the other hand, attempt to shift the science-policy relationship by criticising it. The former called for scientists to acknowledge that scientific clarity is not always functional, while the latter called for scientific assessments to build on different justifications than the policies they are trying to inform, or at least to acknowledge their implicit justifications (for example, the idea that private vehicular use is something which cannot be phased out).

Plurality is tied to the possibility of expressing and hearing multiple voices, something which was missing from the work presented. The absence of participatory processes was one this thesis' main limitations. This was due to lack of time, lack of expertise, and lack of interest at the very start of my Ph.D. (not including participatory processes in my research plan). I assisted in running two engagement events related to the electric vehicle case study[22], and through dissemination events (all listed in the CV of Append A4) I engaged with different audiences on my research topics, but never in a systemic way informed by available expertise. The absence of this "opening up" to wider audiences is felt in the context of my focus on relational complexity, given that I build on the notion that different actors will have different perspectives of the same issue. While I plan to move away from focusing on the science-policy interface in future work, my next research steps will attempt to intentionally include plurality (of concerns, of perceptions and representations) from their inception. The second main limitation is at the level of numerical assessments. First, there is a lack of uncertainty ranges associated with the quantitative results. This is not due to lack of trying. Rather, I struggled to operationalise a global sensitivity analysis associated with data values coming from multiple sources, combined with benchmarks and assumptions, and scaled across levels. My doubts were also associated with the purpose of the analysis (asking myself: Which types of uncertainty are relevant to the numbers I am presenting?). This leads to the second issue requiring improvement with respect to numbers, i.e., the question of how to balance the coupled purpose of presenting methodological advancements (how to address a given scientific issue) while also presenting numerical results (the resulting representation of the chosen scientific issue). This is a balance I did not quite strike, and one that I hope to improve on. While it has brought me to face these limitations, I value the "learning by doing" approach that I experimented with during these past years. The resulting (sometimes messy) trajectory has brought me to a place where I feel well-equipped to undertake new questions and directions in a more structured way.

Looking back at the role played by my results in the context of science-policy relations, I hope to continue along this trajectory by zooming out of the domain of science for policy to that of science in society. This means focusing on the diffuse and possibly more radical impacts that science may have in shaping the type of governance needed to handle wicked sustainability problems, rather than in providing direct advice to institutions. Adaptive governance calls for governance structures that are able to adapt what they do when faced with uncertain and ever-changing events. At a higher level, it also calls for the structures themselves to change and transform. This suggests that we should be building systems of governance which can be stable enough to be legitimate, while also being

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[22] For more details on these engagement events, see the MAGIC deliverable on the electric vehicle innovation (Di Felice et al., 2020)

adaptable enough to transform their identity, in ways which may go against their very existence. While far from what the EU has now, I believe that this kind of governance is necessary to address sustainability for what it is, i.e., a process rather than an end-goal.

What happens if the European Green Deal is successful, and we manage to decarbonise the economy by 2050? Will sustainability be statically achieved? In my view, target-based sustainability policies inevitably miss the mark, focusing on regulating a single output or dimension, rather than trying to understand and govern the processes of evolution and adaptation of social-ecological systems across scales. Astra Taylor views democracy as a process in constant tension, rather than an endpoint (Taylor, 2019). As such, it is something that needs to be fought for continuously. The same holds for sustainability. There is no such thing as a sustainable society, but only a society which constantly seeks sustainability in a just way, managing the process with ethics and humility. Tensions are inevitable. They arise in relation to which social practices we should maintain and which ones we should give away with, in relation to who gets to decide and in relation to how decisions are implemented in practice. These processes inevitably generate winners and losers. Looking back at the European Green Deal, I mentioned in the Introduction of this thesis how its goal is to protect the economy, citizens and the environment, in a win-win-win fashion. Jasanoff (2007) warns against win-win solutions, as they assume "(…) in binary logic, that for each party to a game, winning and losing are the only options" (p.34). This shift to more nuanced understandings of values, trade-offs and tensions must also take place within the process of scientific production.

In this view, collective reflections on how to weave scientific knowledge throughout the processes of sustainability become fruitful and necessary. If governance is to be adaptive in the deepest sense, with governance structures changing their identities and ways of being in response to an increasingly complex world, knowledge that is uncomfortable for existing institutions becomes knowledge that is useful for society. The breadth of uncomfortable knowledge generated within the MAGIC project, then, may be part of bigger shifts in the never-ending processes of sustainability.

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Appendix

A1. Supplementary tables for Chapter 2

Table 12. Structural processors for the case study of Catalonia, with data sources

Type	Orientation	Label	Value	Unit	Source
Nuclear PWR	input	Electricity	44813	kWh/GWh	ICAEN (2012)
Nuclear PWR	input	Fuels	89968	MJ/GWh	Diaz-Maurin and Giampietro, 2013
Nuclear PWR	input	Water	50	m3/GWh	ANAV, 2012
Nuclear PWR	input	Human Activity	65	hrs/GWh	ANAV, 2012
Nuclear PWR	input	Power Capacity	131	kW/GWh	Diaz-Maurin and Giampietro, 2013
Nuclear PWR	input	Land Use	0.004	ha/GWh	NEI, 2015
Nuclear PWR	output	GHG emissions	-	-	-
Natural Gas Combined Cycle (CC)	input	Electricity	26000	kWh/GWh	ICAEN (2012)
Natural Gas Combined Cycle (CC)	input	Fuels	0	MJ/GWh	PRTR, 2017
Natural Gas Combined Cycle (CC)	input	Water	650	m3/GWh	Dones et al., 2007
Natural Gas Combined Cycle (CC)	input	Human Activity	6	hrs/GWh	benchmark
Natural Gas Combined Cycle (CC)	input	Power Capacity	493	kW/GWh	ICAEN (2012)
Natural Gas Combined Cycle (CC)	input	Land Use	0.022	ha/GWh	NEI, 2015
Natural Gas Combined Cycle (CC)	output	GHG emissions	461110	kg CO2 eq./GWh	Dones et al., 2007
Combined Heat & Power (CHP)	input	Electricity	32537	kWh/GWh	ICAEN (2012)
Combined Heat & Power (CHP)	input	Fuels	747762	MJ/GWh	ICAEN (2012)
Combined Heat & Power (CHP)	input	Water	630	m3/GWh	Dones et al., 2007
Combined Heat & Power (CHP)	input	Human Activity	305	hrs/GWh	ACOGEN, 2010
Combined Heat & Power (CHP)	input	Power Capacity	178	kW/GWh	ICAEN, 2012
Combined Heat & Power (CHP)	input	Land Use	0.015	ha/GWh	ACOGEN, 2010
Combined Heat & Power (CHP)	output	GHG emissions	362901	kg CO2 eq./GWh	Dones et al., 2007
Small Hydro (<5 MW)	input	Electricity	13739	kWh/GWh	ICAEN (2012)
Small Hydro (<5 MW)	input	Fuels	0	MJ/GWh	Flury et al., 2012
Small Hydro (<5 MW)	input	Water	0	m3/GWh	Dones et al., 2007
Small Hydro (<5 MW)	input	Human Activity	25	hrs/GWh	benchmark
Small Hydro (<5 MW)	input	Power Capacity	355	kW/GWh	ICAEN (2012)
Small Hydro (<5 MW)	input	Land Use	0.0056263	ha/GWh	Dones et al., 2007
Small Hydro (<5 MW)	output	GHG emissions	0	kg CO2 eq./GWh	Dones et al., 2007
Regular Hydro (>5 MW)	input	Electricity	14988	kWh/GWh	ICAEN (2012)
Regular Hydro (>5 MW)	input	Fuels	0	MJ/GWh	Flury et al., 2012
Regular Hydro (>5 MW)	input	Water	29	m3/GWh	Dones et al., 2007
Regular Hydro (>5 MW)	input	Human Activity	50	hrs/GWh	benchmark
Regular Hydro (>5 MW)	input	Power Capacity	760	kW/GWh	ICAEN (2012)

Regular Hydro (>5 MW)	input	Land Use	0.02300	ha/GWh	Dones et al., 2007
Regular Hydro (>5 MW)	output	GHG emissions	412	kg CO2 eq./GWh	Dones et al., 2007
Pumped Hydro Storage (PHS)	input	Electricity	14988	kWh/GWh	ICAEN (2012)
Pumped Hydro Storage (PHS)	input	Fuels	0	MJ/GWh	Flury et al., 2012
Pumped Hydro Storage (PHS)	input	Water	160.2496981	m3/GWh	Dones et al., 2007
Pumped Hydro Storage (PHS)	input	Human Activity	50	hrs/GWh	benchmark
Pumped Hydro Storage (PHS)	input	Power Capacity	550	kW/GWh	ICAEN (2012)
Pumped Hydro Storage (PHS)	input	Land Use	0.026	ha/GWh	Dones et al., 2007
Pumped Hydro Storage (PHS)	output	GHG emissions	420	kg CO2 eq./GWh	Dones et al., 2007
On-shore Wind Power	input	Electricity	22303	kWh/GWh	ICAEN (2012)
On-shore Wind Power	input	Fuels	0	MJ/GWh	--
On-shore Wind Power	input	Water	0	m3/GWh	--
On-shore Wind Power	input	Human Activity	120	hrs/GWh	ICAEN (2012)
On-shore Wind Power	input	Power Capacity	468	kW/GWh	Budia et al. (2013)
On-shore Wind Power	input	Land Use	12	ha/GWh	Budia et al. (2013)
On-shore Wind Power	output	GHG emissions	0	kg CO2 eq./GWh	--
Solar PV	input	Electricity	0	kWh/GWh	ICAEN, 2012a
Solar PV	input	Fuels	0	MJ/GWh	--
Solar PV	input	Water	0	m3/GWh	--
Solar PV	input	Human Activity	440	hrs/GWh	APPA, (2012)
Solar PV	input	Power Capacity	856	kW/GWh	ICAEN (2012)
Solar PV	input	Land Use	3	ha/GWh	APPA, (2012)
Solar PV	output	GHG emissions	0	kg CO2 eq./GWh	--
Tarragona refinery	input	Electricity	827	kWh/TJ	PRTR, 2017
Tarragona refinery	input	Fuels	3529	MJ/TJ	PRTR, 2017
Tarragona refinery	input	Water	14	m3/TJ	PRTR, 2017
Tarragona refinery	input	Human Activity	4	hrs/TJ	PRTR, 2017
Tarragona refinery	input	Power Capacity	N/A	kW/TJ	PRTR, 2017
Tarragona refinery	input	Land Use	0.000841	ha/TJ	PRTR, 2017
Tarragona refinery	output	GHG emissions	4410	kg CO2 eq./TJ	PRTR, 2017
Tarragona refinery	input	Total refinery output	527051	TJ	PRTR, 2017

A2. Supplementary tables for Chapter 4

Table 13. Selected policy documents. "Code" refers to a short code used by the authors to reference documents

Type	Name	Year	EC code	Code
Directive	on the promotion of clean and energy efficient road transport vehicles	2009	2009/33/EC	dr09
Communication	Action Plan on Urban Mobility	2009	COM(2009) 490 final	um09
White paper	Roadmap to a Single European Transport Area - Towards a Competitive and Resource Efficient Transport System	2011	COM(2011) 144 final	wp11
Communication	Clean Power for Transport: a European Alternative Fuels Strategy	2013	COM(2013) 17 final	cp13
Directive	on the deployment of alternative fuels infrastructure	2014	2014/94/EU	af14
Communication	A European Strategy for Low Emission Mobility	2016	COM(2016) 501 final	lem16
Staff Working Document	Accompanying: "A European Strategy for Low Emission Mobility"	2016	SWD(2016) 244 final	swd16
Communication	Clean Energy for All Europeans	2016	COM(2016) 860 final	ce16
Communication	A European Strategy on cooperative Intelligent Transport Systems, a milestone towards cooperative, connected and automated mobility	2016	COM(2016) 766 final	cit16
Directive	on the promotion of the use of energy from renewable sources (recast)	2018	2018/2001	ren18
Directive	amending Directive 2002/27/EU on energy efficiency	2018	2018/2002	ef18
Directive	on common rules for the internal market for electricity and amending Directive 2012/27/EU	2019	2019/944	im18

Table 14. Keywords used for the literature review

Justification narrative domain	Search queries*
Economic benefits	("electric car(s)" OR "electric vehicle(s)") AND ("jobs" OR "industry" OR "manufacturing" OR "labour" OR "labor" OR "market" OR "job impact" OR "labour impact" OR "labor impact")
GHG emissions	("electric car(s)" OR "electric vehicle(s)") AND ("GHG emissions" OR "environmental impact" OR "CO2 emissions" OR "carbon" OR "LCA" OR "LCI" OR "global emissions" OR "environment")
Security & material requirements	("electric car(s)" OR "electric vehicle(s)") AND ("lithium" OR "cobalt" OR "materials" OR "battery(ies)" OR "imports" OR "security")
	("lithium" OR "cobalt") AND ("impacts" OR "conflicts" OR "reserves" OR "impacts")
Citizen wellbeing	("electric car(s)" OR "electric vehicle(s)") AND ("local pollutants" OR "pollution" OR "pollutants" OR "health" OR "noise" OR "wellbeing")

Table 15. Frequency and references of electric vehicle narratives

	Aggregate node	Frequency	Details	Frequency	Reference documents
WHY: Justifications	Economy, industry & jobs	9	recovery of the European economy	1	um09
			boost economic growth	2	cp13; cp13
			competitiveness of EU industry	4	wp11; um09; cp13; cp13
			produce jobs	2	cp13
	Global Environment	5	reduce GHG of transport	6	cp13; wp11; af14; af14; af14; im18
	Citizen wellbeing	7	health benefits	2	wp11; um09
			improved air quality & noise pollution	5	wp11; wp11; wp11; cp13; af14
	Security	8	savings on oil import bill	1	cp13
			break dependence on oil	5	wp11; cp13; wp11; af14; um09
			improve security of supply	2	cp13; cp13
HOW: measures	Citizens and their behaviour	5	creating sufficient demand	1	dr09
			internalisation of costs leading to behavioural changes	1	um09
			addressing consumer acceptance	1	cp13
			make users aware of benefits / indicate emissions of different transport modes	2	lem16; lem16
	Infrastructure	10	add/improve charging infrastructure	10	wp11; cp13; cp13; cp13; af14; af14; swd16; lem16; lem16; im18
	Financial measures	2	incentives (supply and demand)	1	lem16
			tax instruments	1	lem16
	Regulatory frameworks & interoperability	7	investment friendly regulatory framework	1	cp13
			development of common technical specifications, interoperability	6	cp13; lem16; lem16; lem16; af14; lem16
	Technological advancements	3	domestic production of battery cells	3	cp13; af14; lem16

A3. Supplementary material for Chapter 5

A3.1 Assumptions and data sources

For structural processors, data sources for each input and output are included in the Zenodo database (Di Felice, 2020). When “benchmark” is listed as a data source, information about the specific structure was not available, and a generic benchmark was applied as a placeholder. Ecoinvent data sources for each process are also included, referencing the technology, country and year. Assumptions in handling the data from these sources follow.

A3.1.1. Mapping from the Ecoinvent database

The Ecoinvent database (Frischknecht et al., 2005) was used for input and output data of most structural processors, for water inputs and outputs and GHG outputs, and sometimes for electricity and fuel consumption. For electricity, the electricity inputs listed in Ecoinvent were summed into one aggregate of “electricity consumption”, while fuels were taken without manipulation. Greenhouse gases were converted into their CO_2 equivalent using Global Warming Potentials (GWPs) over a 100-year horizon (GWP100), as reported by the IPCC (Intergovernmental Panel on Climate Change, 2007), and summed into a single output. For water, the Ecoinvent database provides the following categories of water inputs and outputs of energy processes:

1. Input1: water, cooling, unspecified natural origin (in m^3), under the category Elementary flows/resource/in water:
2. Input2: water, decarbonised, at user (in kg), under the category E:Water supply; sewerage, waste management and remediation activities/36:Water collection, treatment and supply/360:Water collection, treatment and supply/3600:Water collection, treatment and supply;
3. Input3: water, completely softened, from decarbonised water, at user (in kg), under the category E:Water supply; sewerage, waste management and remediation activities/36:Water collection, treatment and supply/360:Water collection, treatment and supply/3600:Water collection, treatment and supply;
4. Output1: water (in m3), under the category Elementary flows/Emission to water/unspecified
5. Output2: water (in kg), under the category Elementary flows/Emission to air/unspecified

Inputs and outputs are converted to litres. Input1 is mapped onto the MuSIASEM category of “water_bio”; Input2 and Input3 are summed and mapped onto “water_techno”. Output1 is mapped onto the output “water_bio”. Output2 is excluded from the processor, as it is the water evaporated during the process (i.e., total inputs minus total outputs).

A3.1.2. Other general assumptions

- Labour: For each data point on human activity (for which there are mixed data sources for each processor), employment figures are converted into hours by assuming an average of 1800 working hours per year. Only direct employment is considered (e.g., operation and maintenance of power plants);
- Land use for PES conversion processes, apart from wind turbines, solar panels and hydropower, is considered to be negligible

A3.1.3. Process-specific assumptions

Natural gas turbines

Data on water inputs and outputs and GHG emissions were taken from Ecoinvent. Electricity use is taken from the ICAEN database "dades producciò electrica" (data on electricity production), from the year 2014. The database was filtered for instances of "cicles combinats de gas natural servei public" (natural gas combined cycle for public service). The self-consumption of electricity (CP - Consums propis d'energia elèctrica) was divided by the gross electricity production (PB - Producció bruta d'energia elèctrica). Human activity is based on the natural gas combined cycle plant of Algericas, in Spain, where there are 39 employees for the production of 578772 MWh, according to data from the Spanish Registry of Emissions (PRTR España, 2012). All data is converted per output of MJ of electricity.

CHP

Data for PES inputs are taken from Eurostat, aggregating transformation inputs for both autoproducer and main activity producer CHP plants. For Spain, all CHP plants are aggregated onto a single processor (CHP Spain). The electricity consumed by CHP plants is available through national energy balances (Ministerio para la Transición Ecológica y el Reto Demográfico, 2018) and GHG emissions are taken from a report by the REE (Red Eléctrica Española (REE), 2018). All data (Eurostat + national statistics) is from 2018. For Sweden, individual processors are built for specific CHP processes. For details on this, see the next sub-section "Biomass and waste in Sweden". Added CHP plants for the EU analysis were necessary: coal CHP, lignite CHP and natural gas CHP. For each of these, inputs were taken directly from Eurostat transformation inputs (aggregating autoproducer CHP with main activity producer CHP). Heat outputs were also taken from Eurostat. For natural gas CHP, other inputs and outputs (water, GHG emissions) were taken from Ecoinvent. For coal and lignite, benchmarks for natural gas CHP were used.

Biomass and waste in Sweden

Biomass and waste-to-energy in both boilers and CHP are typical parts of the district heating system in Sweden, accounting for 67% of the input energy. Four processors cover a substantial part of the district heating in Sweden: biomass CHP, waste CHP, biomass heat boilers and waste heat boilers. For human activity, an average EMR for all district heating is assessed, using data on workers and on energy output from the Stockholm Exergi company (Stockholm Exergi, 2018). The EMR is then used to calculate the human activity of each technology. In the case of boilers this is straightforward, whereas for CHP we have to take into account that there are two outputs: electricity and heat. Moreover, the power-to-heat ratio is different and variable depending on the specific technology. Therefore, we use specific power-to-heat ratios. For biomass input, values of are given in "as received" kg, calculated from the values of input energy multiplied by the net calorific values (Sipilä, 2015). These feedstocks come mainly as residues from other systems and are not homogeneous. For waste output, data is given as a share of the feedstock input (Avfall Sverige, 2018; Sipilä, 2015). Water use for all technologies was taken from Ecoinvent. This is specific to the technology mix encountered in Switzerland in 2010 of municipal waste incineration facilities generating both heat and electricity. The data in the inventory has a functional unit of 1kWh of electricity. Therefore, it had to be re-scaled to the total energy output via the power to heat ratio of the specific technology described in the inventory. Greenhouse gas emission factors are derived from the national inventory of Sweden for 2017, more specifically, Table1.A(a)s1 and items 1.A.1.a.ii Combined heat and power generation/biomass and 1.A.1.a.iii Heat plants/biomass (Naturvårdsverket, 2019). Data were not available for waste incineration as a disaggregated category.

Solar PV

Data on land conversion are not available from the Ecoinvent database. Instead, we use data provided by the NREL (Ong et al., 2013). Note that land use requirements for solar panels can vary greatly depending on the architecture of the installation. We take the value for the NREL average for Large PV (<20 MW), which is lower than the one for smaller PV. The value of 3.4 acres/GWh/year is converted into hectares/MWh. The value is an average over PV installations in the US, increasing its robustness. Data on water inputs and outputs are taken from Ecoinvent (see Ecoinvent assumptions above). Electricity consumption is taken from the ICAEN database, as explained for Natural Gas Turbines. The data point is from 2010, as data on self-consumption of solar PV is not available in the database after that year. Human activity is estimated from the IRENA 2017 report on Renewable Power Generation Costs (IRENA, 2018), where it is stated that "The person-days required for the first year of O&M is estimated to be 13,560 for a 50 MW plant". Assuming a utilization factor (UF) of 850 kW/GWh (taken from the average of Catalonia for the year 2012 (ICAEN, 2012) and 1800 working hours per year, the data point is converted into hours per MJ produced.

Wind turbines

Similar to solar PV, given the lack of land conversion data from the Ecoinvent database, we use data from the NREL (Denholm et al., 2009). Land use requirements for wind turbines can vary greatly on the architecture of the installation (e.g., single string vs. multiple string configuration). We only consider the permanent, direct impact area which is occupied. The average area requirements by NREL are provided in hectare/MW, with an average value of 0.3 ± 0.3. We convert the value to ha/MJ, assuming an average utilization factor for wind turbines of 25%. The resulting value is one order of magnitude smaller that land used for solar PV. Data on water inputs and outputs are taken from Ecoinvent. Electricity consumption is taken from the ICAEN database, as explained for Natural Gas Turbines. The data point is from 2013 (latest available data). Human activity is estimated from the IRENA 2017 report on Renewable Power Generation Costs (IRENA, 2018), as above, using a total employment for O&M of wind farms of 2665 person-days per year for a wind farm of MW, and a utilization factor of 25%.

Hydropower

Water flows through hydropower turbines are taken from Ecoinvent. Land use data are taken from Ecoinvent. For run-of-river, the two inputs "Transformation, from pasture and meadow" and "Transformation, from shrub land, sclerophyllous" are summed and converted from m2/kWh to hectares/MJ. For reservoir hydro, the "Transformation, from unknown" input is converted from m2/kWh to hectares/MJ. Electricity consumption by both types of hydro is taken from (Flury et al., 2012). Human activity is estimated from a benchmark provided by a hydroelectricity engineer working at Endesa (personal communication).

Nuclear plant

Water and GHG emissions are taken from Ecoinvent. Electricity input data is taken from ICAEN and converted into MJ. Human activity is estimated from (Nea-iaea, 2018): "For 50 years of operation, annually there are approximately 600 administrative, operation and maintenance, and permanently contracted staff, or about direct 30 000 labour-years during operation". To convert to hours per electrical output, a UF of 90% is assumed (and 1800 hours of labour per year, as everywhere else). For spent nuclear fuel, we only consider highly radioactive spent fuel. Data from the World Nuclear Association (World Nuclear Association, 2018) is converted from extensive (a 1000-MW plant produces 27 tonnes of spent nuclear fuel per year – we assume 90% UF and convert this to spent nuclear fuel output/MJ).

Petroleum products plant

Water, coal and fuel inputs, as well as GHG emissions, were calculated from Ecoinvent. Electricity inputs were taken from ICAEN, following the same logic used for Natural Gas Turbines. Human activity was calculated by using US statistics on employment in the energy sector (US Department of Energy, 2017), combined with US statistics on oil product electricity production (EIA, 2018) in order to reach an intensive data point (following the labour assumptions listed above).

Coal power plant

Water, coal and fuel inputs, as well as GHG emissions, were calculated from Ecoinvent. Electricity inputs were taken from ICAEN, following the same logic used for Natural Gas Turbines. Human activity was calculated by using US statistics on employment in the energy sector (US Department of Energy, 2017), combined with US statistics on coal electricity production (EIA, 2018) in order to reach an intensive data point (following the labour assumptions listed above).

Lignite power plant

Water inputs and outputs and GHG outputs were taken from Ecoinvent. For fuels, electricity and human activity, the benchmark from coal power plants was used.

Natural gas heat boiler

Water, fuel, electricity and GHG were taken from Ecoinvent. Natural gas inputs were taken from Eurostat (transformation input of natural gas into "heat production only", summing autoproducer and main activity producer). For human activity, the benchmark from Swedish waste and biomass heat boilers was used (rounding down the value to 0.001 hrs per MJ of heat.

Coal heat boiler

Water, fuel, electricity and GHG were taken from Ecoinvent. Coal inputs were taken from Eurostat (transformation input of hard coal into "heat production only", summing autoproducer and main activity producer). For human activity, the benchmark from Swedish waste and biomass heat boilers was used (rounding down the value to 0.001 hrs per MJ of heat.

Coke ovens

Data on water, fuels, electricity and GHG emissions for coke ovens comes from the "coking" process in the Ecoinvent database 2.2. Two calculation steps had to be performed to get the processor values:

1. Undo the energy allocation that was made to coke. This is, the total resource use and outputs are not considered, only the 79.8% that is the energy content of coke related to the total output. This was done by dividing all values by 79,8%. The coke oven gas is a 15% of the total energy output.
2. Then, to have the output in mass (kg) we use the net calorific value of coke oven coke from Eurostat manual for energy balances (Eurostat, 2019).

Human activity was assumed to be negligible for this structure.

Uranium mining

Land use data are taken from Ecoinvent. Note that, similar to electricity production, land use inputs are not discounted over the lifetime of the mine/plant but expressed per output per year. Water, GHG emissions and fuel consumption are taken from Ecoinvent for each type of uranium mining (underground, open pit and in-situ leaching). For human activity, employment data from specific mines/countries are used: Wyoming for in-situ leaching (300 people employed to produce 1.3 million pounds of uranium in 2012) and data from Canada for open-pit mining and underground mining, where we assume that similar employment numbers hold (data is at the level of Canada as a whole, which has a mix of underground and open-pit mining).

Nuclear fuel element

We combine three steps into the same processor: refinement of uranium, production of MOX, and production of nuclear fuel element (MOX + refined uranium). For this, Ecoinvent data on the three processes is combined and aggregated (for water, fuel consumption and GHG emissions). For human activity, employment data from the White Mesa Mill is converted to hours/tonnes (Energy Fuels, 2020).

Coal mining

Water inputs and outputs, GHG emissions, fuel and electricity inputs are taken from the Ecoinvent database, following the same assumptions outlined above. For underground coal mining, Data for Europe have been taken directly from Western Europe underground coal mining in Ecoinvent. For open-pit mining, the results presented are the average between five different geographic location contained in Ecoinvent: Russia, South America, Africa, Australia, North America. For human activity, data from the European Association from Coal and Lignite were used (European Association for Coal and Lignite, 2020), scaling employment data by coal production in Europe.

Lignite mining

Water inputs and outputs, GHG emissions, fuel and electricity inputs are taken from the Ecoinvent database, following the same assumptions outlined above. For human activity, data from the European Association from Coal and Lignite were used (European Association for Coal and Lignite, 2020), scaling employment data by lignite production in Europe.

Gas extraction

The NREL LCA server was used for data on water inputs, gas inputs and GHG emissions, for both onshore and offshore gas extraction. The land used for onshore gas extraction was taken from Schori and Frischknecht (2012).

Oil production and refining

Data for oil production and refining processors are from the Oil-Climate Index database, available through Carnegie Endowment for International Peace (2020). Specifically, OPGEE_v1.1_draft_e (downloadable at https://eao.stanford.edu/research-areas/opgee) is the source for oil production processors, while data for refining processors are from PRELIM v.1.2 (https://www.ucalgary.ca/lcaost/prelim). For oil production, from the OPGEE database (75 oil fields), 71 fields were selected, excluding Canadian tar sands, and crudes were sorted by API gravity (light, medium or heavy) and location (onshore or offshore), identifying six types of oil extraction processors:

- Light and onshore.
- Light and offshore.
- Medium and onshore.
- Medium and offshore.
- Heavy and onshore.
- Heavy and offshore crude production.

Intervals of reference for API gravity are those established in the same OPGEE model (see OPGEE_documentation_v1.1e). Data were reported directly from the OPGEE model with default setting: no change in any modelling parameter for oil production was performed. Once data for the oil production types were obtained, they were translated into the established MuSIASEM categories. For human activity in oil extraction, the same benchmark was applied across all oil extraction technologies. The benchmark was calculated from US employment statistics in oil extraction (U.S. Bureau of Labor Statistics, 2020), scaled by total oil output in the US (U.S. Energy Information Administration (EIA), 2020). For refineries, data were collected from PRELIM v.1.2 for each refinery, from the "Main input & output" sheet. Default settings were maintained. From the 129 refineries reported, four main refining processors were constructed:

- Hydroskimming refining.
- Medium conversion refining.
- Deep conversion refining, with coking facilities.
- Deep conversion refining, with hydrocracking facilities.

Each refinery presents one of these configurations, depending on the crude processed and the oil products required as an output.

Biodiesel and bioethanol refineries

Water, GHG emissions, electricity and fuel input were taken from Ecoinvent. Natural gas was converted from MJ to m^3 via its specific energy content (38.7 MJ/m3). As the functional unit was given in 1kg of biofuel output, all values had to be re-scaled to 1MJ. This was done by dividing all values by the specific energy of biofuels: 37.80MJ/kg. For human activity, data from the Neste Oil Renewable Diesel plant in Rotterdam were used, applying the same benchmark to biodiesel and bioethanol (Neste, 2011), using the labour approximation listed above.

Other processors

In addition to the main structural processors, additional ones were added to account for the leftover mix of heat and electricity production (where no individual fuel produced more than 5% of its functional group). These include: Other Electricity Spain; Other CHP Sweden; Other Heat Boilers Sweden; Other Electricity EU; Other CHP EU; Other Heat Boilers EU. For each of these processors, transformation inputs were taken directly from Eurostat. For other inputs and outputs, generic benchmarks were used, taken from average CHP, electricity or heat boiler structures.

A3.1.4. Scaling flows

We refer to "scaling flows" as those extensive output flows needed to pass from an intensive to an extensive description, (e.g., from the GHG emissions per tonne of coal mined, to the GHG emissions for the coal mined in Spain in 2018). Most of these flows are obtained via Eurostat, although some manipulation is often necessary to fit our data organisation. Eurostat provides structural descriptions for the extraction of solid fossil fuels (open-pit vs. underground) and for types of electricity production. For other extraction processes, secondary sources are combined with Eurostat. In terms of externalisation, some approximations are used to determine the structural processes used elsewhere to produce what is imported into Spain, Sweden and the EU. Statistics on provenance of imports and statistics on the structural mix used in exporting countries are combined, where possible, to provide a reasonable description of externalisation. Externalised products refer both to what is imported directly (e.g., direct coal imports) and to what is imported indirectly (e.g., the coal used to produce imported coking coal). Since indirect imports tend to be minor compared to direct ones, we assume that the approximate structural mix for direct imports also applies to indirect ones (the mix is applied to the whole category of "externalized imports"). Heat is never imported/exported, and we assume that electricity imports are negligible for Spain, Sweden and the EU.

Below, the methods used to calculate transformation flows for each product group (using Eurostat product categories) are specified. All sources are included in the Zenodo database under the tab "scaling flows".

Solid fossil fuels

This category refers to coal, lignite and coke oven coke (hard coal, brown coal and coke oven coke, respectively, in the Eurostat commodity balances). Eurostat provides the structural mix for local lignite mining (which is all surface mining, what we refer to as open-pit). Virtual coal imports refer to the coal used to produce the direct imports of coke oven coke. For local coke ovens, Eurostat provides data of transformation inputs (coal) and outputs (coke oven coke and manufactured gases). We assume that the same mix applies to imported coke oven coke. Total externalized coal is the sum of direct coal imports and virtual coal imports. We then apply the same structural mix to the whole group of externalized inputs. European benchmarks are used to assume provenance of imports for Spain, Sweden and the EU. The BP Statistical Review of World Energy (2019) provides the country groups from which Europe imports coal. We only consider the main groups: US, Colombia, Russia and Australia, approximating their relative ratio to the total imports. Various sources are used to approximate structural mix at provenance, as specified in the database. We assume that the structural mix of exporting countries applies directly to all imported products – e.g., if coal mined in Russia is 70% open-pit and 30% underground, we assume that coal imports from Russia were produced with the same 70-30 split.

Gas

The process here is very similar to the one for solid fossil fuels. Neither Spain nor Sweden extract natural gas (extraction in Spain is negligible). There are no imports of secondary gas products (since electricity imports are assumed to be negligible), therefore there are no virtual gas imports. To determine the structural mix of externalized gas extraction, similar to solid fossil fuels the BP Statistical Review of World Energy (2019) is used to determine import provenance for natural gas (including LNG), and various sources are used to determine the structural mix at the exporting countries (all specified in the database). The benchmark for imports into Europe is used, and only the main groups are considered (applying their ratio to the whole group of externalized imports). For gas imports into Europe, this includes Algeria, Norway, Qatar and Nigeria. For lack of specific data, we assume that all gas in Qatar and Nigeria is extracted onshore. The resulting structural mix is in line with global averages (of approximately 2:1 onshore-offshore, as reported by EnergyFiles – source included in database).

For gas extraction in the EU, data is taken from the EU Offshore Authorities Group (2020) who provide statistics of the on-shore and off-shore split of gas extraction in the EU.

Oil & petroleum products

For crude oil and for petroleum products, Eurostat is used to assess production and imports. Virtual imports of oil are those used to produce imported petroleum products.

Total externalized imports refer to direct and virtual imports. Petroleum products are only imported directly. To estimate the share of crude oil needed to produce imported petroleum products, the actual share for local production of Spain, Sweden and the EU is used (derived from Eurostat statistics of transformation inputs and outputs of refineries). The BP Statistical Review of World Energy (2019) is used to estimate provenance of imports for both oil and petroleum products, once again using the benchmark for Europe and applying it to Spain, Sweden and the EU. The exporting groups included for crude oil are Russia, Iraq, Saudi Arabia, North Africa and West Africa. For petroleum products, we include gasoline, diesel, kerosene, fuel oils, coke and "other products" category, that includes heavy residues or products for alternative uses than fuel (asphalt, waxes). Then, the structural mix of exporting country groups for both oil extraction and refineries is estimated using data from the Oil-Climate Index (Carnegie Endowment for International Peace, 2020) from models OPGEE v1.2 draft (oil extraction) e and PRELIM v1.2 (oil refining). Oil fields for each region were grouped depending on API gravity (light, medium, heavy) and location (onshore, offshore), determining the specific regional share. For West Africa, Nigeria and Angola fields were considered, while North Africa includes Libya and Algeria. Direct oil imports from Eurostat were then distributed across different extraction types.

For oil refining, Eurostat does not provide structural distinctions between refineries. Hence, in order to allocate total refinery output onto structural typologies of refineries, information about refineries in Spain, Sweden and the EU has been collected from "A barrel full" (http://abarrelfull.wikidot.com/european-refineries) and, depending on refinery layout, each plant has been associated with the relative type. Sweden presents a special type of refinery, specifically the Nynashamn Refinery, that is dedicated to production of products other than fuels (asphalts, lubricants, waxes, etc..). Since it is not part of the energy sector, benchmarks for this specific instance have not been calculated. For oil extraction in the EU, a rough estimate of typologies of oil extraction in the EU is calculated by considering the main producers (Norway, UK and Denmark)

Electricity, Heat and CHP

Eurostat provides data on electricity, heat and CHP production by fuel type (transformation inputs and transformation outputs). Fuel type is mapped onto structural categories – e.g., electricity through natural gas is assumed to be produced by natural gas turbines. There is no production of derived heat in Spain. For Sweden and the EU, heat is produced both on its own and in CHP facilities. Heat production on its own is assumed to be carried out via heat boilers and heat pumps. For all transformation inputs and outputs of electricity, heat and CHP, main activity producer and autoproducer activity is aggregated into a single category.

Nuclear chain

Eurostat does not provide data on imports of uranium or nuclear fuel element. From the production of nuclear electricity, we calculate required NFE and required uranium, using our structural processors (see data sources in the database). We only account for uranium and NFE used directly to produce the nuclear electricity output, without considering imports of uranium and NFE that are stored, since the timescale of the analysis is of one year. According to the World Nuclear Association, uranium enrichment in both Sweden and Spain is negligible. Therefore, we assume that all NFE is imported, as well as uranium. For provenance and typology of uranium extraction, data on provenance of

European imports are considered, combined with information on methods of extraction at the main exporting countries (Russia, Kazakhstan, Canada, Niger, Australia and Romania) (both from the WNA – specific sources detailed in database). Since after calculation underground uranium mining only accounts for 5% of imported uranium, we approximate and only include open-pit and ISL uranium mining, with 70% open-pit and 30% ISL. For uranium enrichment, we assume a single structural description/technology, as reported in the database of structural processors.

Eurostat provides data on production of bioethanol and biodiesel. It also provides data on biomass production and imports, but this doesn't include the biomass used as an input for biofuels. For this, we calculate biomass needed for bioethanol and biodiesel production based on our structural processors. We also use this to calculate virtual biomass imports embedded in biofuel imports (direct imports are provided by Eurostat).

Biofuels, biogas and waste

Primary production and imports of biogas and waste are also provided by Eurostat. Similar to bioethanol and biodiesel, primary production of solid biofuels (what we call biomass) does not include inputs to biogas. For this, once again the structural description of processors is used to calculate biomass input. For waste production, renewable and non-renewable waste are aggregated into a single "waste" category (this also applies to waste inputs into other processes). Neither biogas nor biowaste are imported.

A3.1.5. Aggregations

Many energy processes have multiple outputs (e.g., CHP producing both heat and power). We do not allocate inputs and outputs. Instead, we choose which functional aggregation is assigned to each structure depending on context (i.e., which output is the primary one). For Spain and the EU, for example, CHP is aggregated under electricity production, while it is aggregated under heat production for Sweden (as more MJs of heat are produced by CHP plants in Sweden, than MJs of electricity). However, we do not ignore the multiple outputs – this means that, for example, the "electricity production" processor in the EU also has heat as an output (scaled by the primary output of electricity). Aggregations from structural processors onto functional groups are shown in Table 16.

Table 16. Aggregations across levels

child name	parent name	final parent	Country
lignite mining (LOC - ES)	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
underground coal mining (EXT - ES)	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES
open-pit coal mining (EXT - ES)	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES
coke oven (LOC - ES)	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
coke oven (EXT - ES)	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES
on-shore gas extraction, electricity part (EXT - ES)	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES
off-shore gas extraction, electricity part (EXT - ES)	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES
on-shore gas extraction, final consumption part (EXT - ES)	Gas (EXT - ES)	Energy sector (EXT - ES)	ES

off-shore gas extraction, final consumption part (EXT - ES)	Gas (EXT - ES)	Energy sector (EXT - ES)	ES
in situ leaching uranium mining (EXT - ES)	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES
open pit uranium mining (EXT - ES)	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES
onshore light oil extraction (EXT - ES), electricity part	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES
offshore light oil extration (EXT - ES), electricity part	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES
onshore medium oil extraction (EXT - ES), electricity part	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES
offshore medium oil extraction (EXT - ES), electricity part	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES
offshore heavy oil extraction (EXT - ES), electricity part	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES
onshore light oil extraction (EXT - ES), fuels part	Fuels (EXT - ES)	Energy sector (EXT - ES)	ES
offshore light oil extration (EXT - ES), fuels part	Fuels (EXT - ES)	Energy sector (EXT - ES)	ES
onshore medium oil extraction (EXT - ES), fuels part	Fuels (EXT - ES)	Energy sector (EXT - ES)	ES
offshore medium oil extraction (EXT - ES), fuels part	Fuels (EXT - ES)	Energy sector (EXT - ES)	ES
offshore heavy oil extraction (EXT - ES), fuels part	Fuels (EXT - ES)	Energy sector (EXT - ES)	ES
natural gas turbines (LOC - ES)	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
CHP Spain (LOC - ES)	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
solar PV (LOC - ES)	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
wind turbines (LOC - ES)	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
hydro (LOC - ES)	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
pumped hydro storage (LOC - ES)	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
nuclear plant (LOC - ES)	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
coal power plant (LOC - ES)	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
petroleum products plant (LOC - ES)	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
other electricity spain (LOC - ES)	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
hydroskimming refinery (LOC - ES), electricity part	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
medium conversion refinery (LOC - ES), electricity part	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
deep conversion with coking facilities refinery (LOC - ES), electricity part	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
deep conversion with hydrocracking facilities refinery (LOC - ES), electricity part	Electricity (LOC - ES)	Energy sector (LOC - ES)	ES
hydroskimming refinery (LOC - ES), fuels part	Fuels (LOC - ES)	Energy sector (LOC - ES)	ES
medium conversion refinery (LOC - ES), fuels part	Fuels (LOC - ES)	Energy sector (LOC - ES)	ES
deep conversion with coking facilities refinery (LOC - ES), fuels part	Fuels (LOC - ES)	Energy sector (LOC - ES)	ES
deep conversion with hydrocracking facilities refinery (LOC - ES), fuels part	Fuels (LOC - ES)	Energy sector (LOC - ES)	ES
hydroskimming refinery (EXT - ES), electricity part	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES
medium conversion refinery (EXT - ES), electricity part	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES
hydroskimming refinery (EXT - ES), fuels part	Fuels (EXT - ES)	Energy sector (EXT - ES)	ES
medium conversion refinery (EXT - ES), fuels part	Fuels (EXT - ES)	Energy sector (EXT - ES)	ES
deep conversion with coking facilities refinery (EXT - ES), fuels part	Fuels (EXT - ES)	Energy sector (EXT - ES)	ES
deep conversion with hydrocracking facilities refinery (EXT - ES), fuels part	Fuels (EXT - ES)	Energy sector (EXT - ES)	ES
nuclear fuel element plant (EXT - ES)	Electricity (EXT - ES)	Energy sector (EXT - ES)	ES

bioethanol refinery (LOC - ES)	Fuels (LOC - ES)	Energy sector (LOC - ES)	ES
biodiesel refinery (LOC - ES)	Fuels (LOC - ES)	Energy sector (LOC - ES)	ES
bioethanol refinery (EXT - ES)	Fuels (EXT - ES)	Energy sector (LOC - ES)	ES
biodiesel refinery (EXT - ES)	Fuels (EXT - ES)	Energy sector (LOC - ES)	ES
underground coal mining (EXT - SE)	Heat (EXT - SE)	Energy sector (EXT - SE)	SE
open-pit coal mining (EXT - SE)	Heat (EXT - SE)	Energy sector (EXT - SE)	SE
coke oven (LOC - ES)	Heat (LOC - SE)	Energy sector (LOC - SE)	SE
coke oven (EXT - ES)	Heat (EXT - SE)	Energy sector (EXT - SE)	SE
on-shore gas extraction, heat part (EXT - SE)	Heat (EXT - SE)	Energy sector (EXT - SE)	SE
off-shore gas extraction, heat part (EXT - SE)	Heat (EXT - SE)	Energy sector (EXT - SE)	SE
on-shore gas extraction, final consumption part (EXT - SE)	Gas (EXT - SE)	Energy sector (EXT - SE)	SE
off-shore gas extraction, final consumption part (EXT - SE)	Gas (EXT - SE)	Energy sector (EXT - SE)	SE
in situ leaching uranium mining (EXT - SE)	Electricity (EXT - SE)	Energy sector (EXT - SE)	SE
open pit uranium mining (EXT - SE)	Electricity (EXT - SE)	Energy sector (EXT - SE)	SE
onshore light oil extraction (EXT - SE)	Fuels (EXT - SE)	Energy sector (EXT - SE)	SE
offshore light oil extraction (EXT - SE)	Fuels (EXT - SE)	Energy sector (EXT - SE)	SE
onshore medium oil extraction (EXT - SE)	Fuels (EXT - SE)	Energy sector (EXT - SE)	SE
offshore medium oil extraction (EXT - SE)	Fuels (EXT - SE)	Energy sector (EXT - SE)	SE
offshore heavy oil extraction (EXT - SE)	Fuels (EXT - SE)	Energy sector (EXT - SE)	SE
solar PV (LOC - SE)	Electricity (LOC - SE)	Energy sector (LOC - SE)	SE
wind turbines (LOC - SE)	Electricity (LOC - SE)	Energy sector (LOC - SE)	SE
hydro (LOC - SE)	Electricity (LOC - SE)	Energy sector (LOC - SE)	SE
nuclear plant (LOC - SE)	Electricity (LOC - SE)	Energy sector (LOC - SE)	SE
biomass CHP plant (LOC - SE)	Heat (LOC - SE)	Energy sector (LOC - SE)	SE
waste CHP plant (LOC - SE)	Heat (LOC - SE)	Energy sector (LOC - SE)	SE
other chp sweden (LOC - SE)	Heat (LOC - SE)	Energy sector (LOC - SE)	SE
biomass heat boiler (LOC - SE)	Heat (LOC - SE)	Energy sector (LOC - SE)	SE
waste heat boiler (LOC - SE)	Heat (LOC - SE)	Energy sector (LOC - SE)	SE
heat pump (LOC - SE)	Heat (LOC - SE)	Energy sector (LOC - SE)	SE
other heat boilers sweden (LOC - SE)	Heat (LOC - SE)	Energy sector (LOC - SE)	SE
medium conversion refinery (LOC - SE)	Fuels (LOC - SE)	Energy sector (LOC - SE)	SE
deep conversion with hydrocracking facilities refinery (LOC - SE)	Fuels (LOC - SE)	Energy sector (LOC - SE)	SE
hydroskimming refinery (EXT - SE)	Fuels (EXT - SE)	Energy sector (EXT - SE)	SE
medium conversion refinery (EXT - SE)	Fuels (EXT - SE)	Energy sector (EXT - SE)	SE
nuclear fuel element plant (EXT - SE)	Fuels (EXT - SE)	Energy sector (EXT - SE)	SE
bioethanol refinery (LOC - SE)	Fuels (LOC - SE)	Energy sector (LOC - SE)	SE
biodiesel refinery (LOC - SE)	Fuels (LOC - SE)	Energy sector (LOC - SE)	SE
bioethanol refinery (EXT - SE)	Fuels (EXT - SE)	Energy sector (EXT - SE)	SE
biodiesel refinery (EXT - SE)	Fuels (EXT - SE)	Energy sector (EXT - SE)	SE
lignite mining (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
underground coal mining (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
open-pit coal mining (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU

underground coal mining (EXT - EU)	Electricity (EXT - EU)	Energy sector (EXT - EU)	EU
open-pit coal mining (EXT - EU)	Electricity (EXT - EU)	Energy sector (EXT - EU)	EU
coke oven (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
coke oven (EXT - EU)	Electricity (EXT - EU)	Energy sector (EXT - EU)	EU
on-shore gas extraction, electricity part (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
off-shore gas extraction, electricity part (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
on-shore gas extraction, heat part (LOC - EU)	Heat (LOC - EU)	Energy sector (LOC - EU)	EU
off-shore gas extraction, heat part (LOC - EU)	Heat (LOC - EU)	Energy sector (LOC - EU)	EU
on-shore gas extraction, final consumption part (LOC - EU)	Gas (LOC - EU)	Energy sector (LOC - EU)	EU
off-shore gas extraction, final consumption part (LOC - EU)	Gas (LOC - EU)	Energy sector (LOC - EU)	EU
on-shore gas extraction, electricity part (EXT - EU)	Electricity (EXT - EU)	Energy sector (EXT - EU)	EU
off-shore gas extraction, electricity part (EXT - EU)	Electricity (EXT - EU)	Energy sector (EXT - EU)	EU
on-shore gas extraction, heat part (EXT - EU)	Heat (EXT - EU)	Energy sector (EXT - EU)	EU
off-shore gas extraction, heat part (EXT - EU)	Heat (EXT - EU)	Energy sector (EXT - EU)	EU
on-shore gas extraction, final consumption part (EXT - EU)	Gas (EXT - EU)	Energy sector (EXT - EU)	EU
off-shore gas extraction, final consumption part (EXT - EU)	Gas (EXT - EU)	Energy sector (EXT - EU)	EU
in situ leaching uranium mining (EXT - EU)	Electricity (EXT - EU)	Energy sector (EXT - EU)	EU
open pit uranium mining (EXT - EU)	Electricity (EXT - EU)	Energy sector (EXT - EU)	EU
onshore light oil extraction (LOC - EU), fuels part	Fuels (LOC - EU)	Energy sector (LOC - EU)	EU
offshore light oil extraction (LOC - EU), fuels part	Fuels (LOC - EU)	Energy sector (LOC - EU)	EU
onshore medium oil extraction (LOC - EU), fuels part	Fuels (LOC - EU)	Energy sector (LOC - EU)	EU
offshore medium oil extraction (LOC - EU), fuels part	Fuels (LOC - EU)	Energy sector (LOC - EU)	EU
offshore heavy oil extraction (LOC - EU), fuels part	Fuels (LOC - EU)	Energy sector (LOC - EU)	EU
onshore light oil extraction (EXT - EU), fuels part	Fuels (EXT - EU)	Energy sector (EXT - EU)	EU
offshore light oil extraction (EXT - EU), fuels part	Fuels (EXT - EU)	Energy sector (EXT - EU)	EU
onshore medium oil extraction (EXT - EU), fuels part	Fuels (EXT - EU)	Energy sector (EXT - EU)	EU
offshore medium oil extraction (EXT - EU), fuels part	Fuels (EXT - EU)	Energy sector (EXT - EU)	EU
offshore heavy oil extraction (EXT - EU), fuels part	Fuels (EXT - EU)	Energy sector (EXT - EU)	EU
natural gas turbines (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
natural gas chp plant (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
coal chp plant (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
other chp plants EU (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
solar PV (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
wind turbines (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
hydro (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
nuclear plant (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
coal power plant (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
lignite power plant (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU
other electricity EU (LOC - EU)	Electricity (LOC - EU)	Energy sector (LOC - EU)	EU

hydroskimming refinery (LOC - EU)	Fuels (LOC - EU)	Energy sector (LOC - EU)	EU
medium conversion refinery (LOC - EU)	Fuels (LOC - EU)	Energy sector (LOC - EU)	EU
deep conversion with coking facilities refinery (LOC - EU)	Fuels (LOC - EU)	Energy sector (LOC - EU)	EU
deep conversion with hydrocracking facilities refinery (LOC - EU)	Fuels (LOC - EU)	Energy sector (LOC - EU)	EU
hydroskimming refinery (EXT - EU)	Fuels (EXT - EU)	Energy sector (EXT - EU)	EU
medium conversion refinery (EXT - EU)	Fuels (EXT - EU)	Energy sector (EXT- EU)	EU
nuclear fuel element plant (EXT - EU)	Electricity (EXT - EU)	Energy sector (EXT- EU)	EU
bioethanol refinery (LOC - EU)	Fuels (LOC - EU)	Energy sector (LOC - EU)	EU
biodiesel refinery (LOC - EU)	Fuels (LOC - EU)	Energy sector (LOC - EU)	EU
bioethanol refinery (EXT - EU)	Fuels (EXT - EU)	Energy sector (EXT - EU)	EU
biodiesel refinery (EXT - EU)	Fuels (EXT - EU)	Energy sector (EXT - EU)	EU
natural gas heat boiler	Heat (LOC - EU)	Energy sector (LOC - EU)	EU
coal heat boiler	Heat (LOC - EU)	Energy sector (LOC - EU)	EU
biomass heat boiler	Heat (LOC - EU)	Energy sector (LOC - EU)	EU
waste heat boiler	Heat (LOC - EU)	Energy sector (LOC - EU)	EU
other heat boilers EU	Heat (LOC - EU)	Energy sector (LOC - EU)	EU

A3.2. Full biosphere and technosphere matrices

Table 17. Biosphere and technosphere matrices, Spain (2018). Energy sector is an aggregation of the sectors electricity, fuels and gas

Country	Sector	Location	Matrix	Orient.	Label	Value	Unit
ES	Electricity	Local	Technosphere	in	biofuels	0.00E+00	MJ
ES	Electricity	Local	Technosphere	in	biogas	1.13E+10	MJ
ES	Electricity	Local	Technosphere	in	coal products	0.00E+00	kg
ES	Electricity	Local	Technosphere	in	derived heat	0.00E+00	MJ
ES	Electricity	Local	Technosphere	in	electricity	5.13E+10	MJ
ES	Electricity	Local	Technosphere	in	human activity	3.71E+07	hrs
ES	Electricity	Local	Technosphere	in	manufactured gas	7.95E+09	MJ
ES	Electricity	Local	Technosphere	in	nuclear fuel element	1.37E+05	kg
ES	Electricity	Local	Technosphere	in	other hydrocarbons	0.00E+00	kg
ES	Electricity	Local	Technosphere	in	power capacity	2.66E+10	MW
ES	Electricity	Local	Technosphere	in	solid fossil fuels	0.00E+00	kg
ES	Electricity	Local	Technosphere	in	total oil products	1.37E+11	MJ
ES	Electricity	Local	Technosphere	in	waste	3.90E+10	kg
ES	Electricity	Local	Technosphere	in	water_techno	2.80E+11	l
ES	Electricity	Local	Biosphere	in	land use	1.85E+04	ha
ES	Electricity	Local	Biosphere	in	water_bio	2.92E+14	l
ES	Electricity	Local	Biosphere	out	biomass	0.00E+00	kg
ES	Electricity	Local	Biosphere	out	coal	0.00E+00	kg

ES	Electricity	Local	Biosphere	out	gas	0.00E+00	m3
ES	Electricity	Local	Biosphere	out	greenhouse gases	7.43E+10	kg CO2 eq.
ES	Electricity	Local	Biosphere	out	lignite	1.63E+09	kg
ES	Electricity	Local	Biosphere	out	oil	0.00E+00	kg
ES	Electricity	Local	Biosphere	out	spent nuclear fuel	1.81E+05	kg
ES	Electricity	Local	Biosphere	out	uranium	0.00E+00	kg
ES	Electricity	Local	Biosphere	out	waste	0.00E+00	kg
ES	Electricity	Local	Biosphere	out	water_bio	2.91E+14	l
ES	Electricity	Externalised	Technosphere	in	biofuels	0.00E+00	MJ
ES	Electricity	Externalised	Technosphere	in	biogas	1.21E+06	MJ
ES	Electricity	Externalised	Technosphere	in	coal products	0.00E+00	kg
ES	Electricity	Externalised	Technosphere	in	derived heat	3.90E+08	MJ
ES	Electricity	Externalised	Technosphere	in	electricity	7.45E+08	MJ
ES	Electricity	Externalised	Technosphere	in	human activity	9.75E+07	hrs
ES	Electricity	Externalised	Technosphere	in	manufactured gas	1.38E+09	MJ
ES	Electricity	Externalised	Technosphere	in	nuclear fuel element	0.00E+00	kg
ES	Electricity	Externalised	Technosphere	in	other hydrocarbons	0.00E+00	kg
ES	Electricity	Externalised	Technosphere	in	power capacity	0.00E+00	MW
ES	Electricity	Externalised	Technosphere	in	solid fossil fuels	0.00E+00	kg
ES	Electricity	Externalised	Technosphere	in	total oil products	1.00E+09	MJ
ES	Electricity	Externalised	Technosphere	in	waste	0.00E+00	kg
ES	Electricity	Externalised	Technosphere	in	water_techno	5.42E+09	l
ES	Electricity	Externalised	Biosphere	in	land use	6.99E+04	ha
ES	Electricity	Externalised	Biosphere	in	water_bio	8.23E+09	l
ES	Electricity	Externalised	Biosphere	out	biomass	0.00E+00	kg
ES	Electricity	Externalised	Biosphere	out	coal	1.63E+10	kg
ES	Electricity	Externalised	Biosphere	out	gas	7.22E+09	m3
ES	Electricity	Externalised	Biosphere	out	greenhouse gases	2.92E+09	kg CO2 eq.
ES	Electricity	Externalised	Biosphere	out	lignite	0.00E+00	kg
ES	Electricity	Externalised	Biosphere	out	oil	2.59E+09	kg
ES	Electricity	Externalised	Biosphere	out	spent nuclear fuel	0.00E+00	kg
ES	Electricity	Externalised	Biosphere	out	uranium	1.29E+05	kg
ES	Electricity	Externalised	Biosphere	out	waste	4.90E+07	kg
ES	Electricity	Externalised	Biosphere	out	water_bio	7.62E+09	l
ES	Electricity	Total	Technosphere	in	biofuels	0.00E+00	MJ
ES	Electricity	Total	Technosphere	in	biogas	1.13E+10	MJ
ES	Electricity	Total	Technosphere	in	coal products	0.00E+00	kg
ES	Electricity	Total	Technosphere	in	derived heat	3.90E+08	MJ
ES	Electricity	Total	Technosphere	in	electricity	5.20E+10	MJ
ES	Electricity	Total	Technosphere	in	human activity	1.35E+08	hrs
ES	Electricity	Total	Technosphere	in	manufactured gas	9.33E+09	MJ
ES	Electricity	Total	Technosphere	in	nuclear fuel element	1.37E+05	kg

ES	Electricity	Total	Technosphere	in	other hydrocarbons	0.00E+00	kg
ES	Electricity	Total	Technosphere	in	power capacity	2.66E+10	MW
ES	Electricity	Total	Technosphere	in	solid fossil fuels	0.00E+00	kg
ES	Electricity	Total	Technosphere	in	total oil products	1.38E+11	MJ
ES	Electricity	Total	Technosphere	in	waste	3.90E+10	kg
ES	Electricity	Total	Technosphere	in	water_techno	2.85E+11	l
ES	Electricity	Total	Biosphere	in	land use	8.84E+04	ha
ES	Electricity	Total	Biosphere	in	water_bio	2.93E+14	l
ES	Electricity	Total	Biosphere	out	biomass	0.00E+00	kg
ES	Electricity	Total	Biosphere	out	coal	1.63E+10	kg
ES	Electricity	Total	Biosphere	out	gas	7.22E+09	m3
ES	Electricity	Total	Biosphere	out	greenhouse gases	7.72E+10	kg CO2 eq.
ES	Electricity	Total	Biosphere	out	lignite	1.63E+09	kg
ES	Electricity	Total	Biosphere	out	oil	2.59E+09	kg
ES	Electricity	Total	Biosphere	out	spent nuclear fuel	1.81E+05	kg
ES	Electricity	Total	Biosphere	out	uranium	1.29E+05	kg
ES	Electricity	Total	Biosphere	out	waste	4.90E+07	kg
ES	Electricity	Total	Biosphere	out	water_bio	2.91E+14	l
ES	Fuels	Local	Technosphere	in	biofuels	0.00E+00	MJ
ES	Fuels	Local	Technosphere	in	biogas	0.00E+00	MJ
ES	Fuels	Local	Technosphere	in	coal products	0.00E+00	kg
ES	Fuels	Local	Technosphere	in	derived heat	0.00E+00	MJ
ES	Fuels	Local	Technosphere	in	electricity	1.34E+10	MJ
ES	Fuels	Local	Technosphere	in	human activity	1.74E+07	hrs
ES	Fuels	Local	Technosphere	in	manufactured gas	2.57E+11	MJ
ES	Fuels	Local	Technosphere	in	nuclear fuel element	0.00E+00	kg
ES	Fuels	Local	Technosphere	in	other hydrocarbons	0.00E+00	kg
ES	Fuels	Local	Technosphere	in	power capacity	0.00E+00	MW
ES	Fuels	Local	Technosphere	in	solid fossil fuels	0.00E+00	kg
ES	Fuels	Local	Technosphere	in	total oil products	1.58E+11	MJ
ES	Fuels	Local	Technosphere	trin	waste	0.00E+00	kg
ES	Fuels	Local	Technosphere	in	water_techno	6.56E+09	l
ES	Fuels	Local	Biosphere	in	land use	0.00E+00	ha
ES	Fuels	Local	Biosphere	in	water_bio	2.31E+10	l
ES	Fuels	Local	Biosphere	out	biomass	0.00E+00	kg
ES	Fuels	Local	Biosphere	out	coal	0.00E+00	kg
ES	Fuels	Local	Biosphere	out	gas	0.00E+00	m3
ES	Fuels	Local	Biosphere	out	greenhouse gases	3.10E+10	kg CO2 eq.
ES	Fuels	Local	Biosphere	out	lignite	0.00E+00	kg
ES	Fuels	Local	Biosphere	out	oil	0.00E+00	kg
ES	Fuels	Local	Biosphere	out	spent nuclear fuel	0.00E+00	kg
ES	Fuels	Local	Biosphere	out	uranium	0.00E+00	kg

ES	Fuels	Local	Biosphere	out	waste	0.00E+00	kg
ES	Fuels	Local	Biosphere	out	water_bio	2.20E+08	l
ES	Fuels	Externalised	Technosphere	in	biofuels	0.00E+00	MJ
ES	Fuels	Externalised	Technosphere	in	biogas	0.00E+00	MJ
ES	Fuels	Externalised	Technosphere	in	coal products	0.00E+00	kg
ES	Fuels	Externalised	Technosphere	in	derived heat	0.00E+00	MJ
ES	Fuels	Externalised	Technosphere	in	electricity	2.93E+09	MJ
ES	Fuels	Externalised	Technosphere	in	human activity	5.77E+07	hrs
ES	Fuels	Externalised	Technosphere	in	manufactured gas	4.46E+10	MJ
ES	Fuels	Externalised	Technosphere	in	nuclear fuel element	0.00E+00	kg
ES	Fuels	Externalised	Technosphere	in	other hydrocarbons	0.00E+00	kg
ES	Fuels	Externalised	Technosphere	in	power capacity	0.00E+00	MW
ES	Fuels	Externalised	Technosphere	in	solid fossil fuels	0.00E+00	kg
ES	Fuels	Externalised	Technosphere	in	total oil products	3.06E+10	MJ
ES	Fuels	Externalised	Technosphere	in	waste	0.00E+00	kg
ES	Fuels	Externalised	Technosphere	in	water_techno	9.64E+10	l
ES	Fuels	Externalised	Biosphere	in	land use	7.78E+04	ha
ES	Fuels	Externalised	Biosphere	in	water_bio	4.05E+10	l
ES	Fuels	Externalised	Biosphere	out	biomass	0.00E+00	kg
ES	Fuels	Externalised	Biosphere	out	coal	0.00E+00	kg
ES	Fuels	Externalised	Biosphere	out	gas	1.12E+10	m3
ES	Fuels	Externalised	Biosphere	out	greenhouse gases	3.09E+10	kg CO2 eq.
ES	Fuels	Externalised	Biosphere	out	lignite	0.00E+00	kg
ES	Fuels	Externalised	Biosphere	out	oil	8.35E+10	kg
ES	Fuels	Externalised	Biosphere	out	spent nuclear fuel	0.00E+00	kg
ES	Fuels	Externalised	Biosphere	out	uranium	0.00E+00	kg
ES	Fuels	Externalised	Biosphere	out	waste	0.00E+00	kg
ES	Fuels	Externalised	Biosphere	out	water_bio	2.30E+08	l
ES	Fuels	Total	Technosphere	in	biofuels	0.00E+00	MJ
ES	Fuels	Total	Technosphere	in	biogas	0.00E+00	MJ
ES	Fuels	Total	Technosphere	in	coal products	0.00E+00	kg
ES	Fuels	Total	Technosphere	in	derived heat	0.00E+00	MJ
ES	Fuels	Total	Technosphere	in	electricity	1.63E+10	MJ
ES	Fuels	Total	Technosphere	in	human activity	7.52E+07	hrs
ES	Fuels	Total	Technosphere	in	manufactured gas	3.02E+11	MJ
ES	Fuels	Total	Technosphere	in	nuclear fuel element	0.00E+00	kg
ES	Fuels	Total	Technosphere	in	other hydrocarbons	0.00E+00	kg
ES	Fuels	Total	Technosphere	in	power capacity	0.00E+00	MW
ES	Fuels	Total	Technosphere	in	solid fossil fuels	0.00E+00	kg
ES	Fuels	Total	Technosphere	in	total oil products	1.89E+11	MJ
ES	Fuels	Total	Technosphere	in	waste	0.00E+00	kg
ES	Fuels	Total	Technosphere	in	water_techno	1.03E+11	l

ES	Fuels	Total	Biosphere	in	land use	7.78E+04	ha
ES	Fuels	Total	Biosphere	in	water_bio	6.36E+10	l
ES	Fuels	Total	Biosphere	out	biomass	0.00E+00	kg
ES	Fuels	Total	Biosphere	out	coal	0.00E+00	kg
ES	Fuels	Total	Biosphere	out	gas	1.12E+10	m3
ES	Fuels	Total	Biosphere	out	greenhouse gases	6.20E+10	kg CO2 eq.
ES	Fuels	Total	Biosphere	out	lignite	0.00E+00	kg
ES	Fuels	Total	Biosphere	out	oil	8.35E+10	kg
ES	Fuels	Total	Biosphere	out	spent nuclear fuel	0.00E+00	kg
ES	Fuels	Total	Biosphere	out	uranium	0.00E+00	kg
ES	Fuels	Total	Biosphere	out	waste	0.00E+00	kg
ES	Fuels	Total	Biosphere	out	water_bio	4.51E+08	l
ES	Gas	Local	Technosphere	in	biofuels	0.00E+00	MJ
ES	Gas	Local	Technosphere	in	biogas	0.00E+00	MJ
ES	Gas	Local	Technosphere	in	coal products	0.00E+00	kg
ES	Gas	Local	Technosphere	in	derived heat	0.00E+00	MJ
ES	Gas	Local	Technosphere	in	electricity	0.00E+00	MJ
ES	Gas	Local	Technosphere	in	human activity	0.00E+00	hrs
ES	Gas	Local	Technosphere	in	manufactured gas	0.00E+00	MJ
ES	Gas	Local	Technosphere	in	nuclear fuel element	0.00E+00	kg
ES	Gas	Local	Technosphere	in	other hydrocarbons	0.00E+00	kg
ES	Gas	Local	Technosphere	in	power capacity	0.00E+00	MW
ES	Gas	Local	Technosphere	in	solid fossil fuels	0.00E+00	kg
ES	Gas	Local	Technosphere	in	total oil products	0.00E+00	MJ
ES	Gas	Local	Technosphere	in	waste	0.00E+00	kg
ES	Gas	Local	Technosphere	in	water_techno	0.00E+00	l
ES	Gas	Local	Biosphere	in	land use	0.00E+00	ha
ES	Gas	Local	Biosphere	in	water_bio	0.00E+00	l
ES	Gas	Local	Biosphere	out	biomass	0.00E+00	kg
ES	Gas	Local	Biosphere	out	coal	0.00E+00	kg
ES	Gas	Local	Biosphere	out	gas	0.00E+00	m3
ES	Gas	Local	Biosphere	out	greenhouse gases	0.00E+00	kg CO2 eq.
ES	Gas	Local	Biosphere	out	lignite	0.00E+00	kg
ES	Gas	Local	Biosphere	out	oil	0.00E+00	kg
ES	Gas	Local	Biosphere	out	spent nuclear fuel	0.00E+00	kg
ES	Gas	Local	Biosphere	out	uranium	0.00E+00	kg
ES	Gas	Local	Biosphere	out	waste	0.00E+00	kg
ES	Gas	Local	Biosphere	out	water_bio	0.00E+00	l
ES	Gas	Externalised	Technosphere	in	biofuels	0.00E+00	MJ
ES	Gas	Externalised	Technosphere	in	biogas	0.00E+00	MJ
ES	Gas	Externalised	Technosphere	in	coal products	0.00E+00	kg
ES	Gas	Externalised	Technosphere	in	derived heat	0.00E+00	MJ
ES	Gas	Externalised	Technosphere	in	electricity	3.13E+08	MJ

ES	Gas	Externalised	Technosphere	in	human activity	1.71E+08	hrs
ES	Gas	Externalised	Technosphere	in	manufactured gas	0.00E+00	MJ
ES	Gas	Externalised	Technosphere	in	nuclear fuel element	0.00E+00	kg
ES	Gas	Externalised	Technosphere	in	other hydrocarbons	0.00E+00	kg
ES	Gas	Externalised	Technosphere	in	power capacity	0.00E+00	MW
ES	Gas	Externalised	Technosphere	in	solid fossil fuels	0.00E+00	kg
ES	Gas	Externalised	Technosphere	in	total oil products	3.75E+06	MJ
ES	Gas	Externalised	Technosphere	in	waste	0.00E+00	kg
ES	Gas	Externalised	Technosphere	in	water_techno	0.00E+00	l
ES	Gas	Externalised	Biosphere	in	land use	8.93E+01	ha
ES	Gas	Externalised	Biosphere	in	water_bio	2.28E+09	l
ES	Gas	Externalised	Biosphere	out	biomass	0.00E+00	kg
ES	Gas	Externalised	Biosphere	out	coal	0.00E+00	kg
ES	Gas	Externalised	Biosphere	out	gas	1.33E+10	m3
ES	Gas	Externalised	Biosphere	out	greenhouse gases	1.56E+09	kg CO2 eq.
ES	Gas	Externalised	Biosphere	out	lignite	0.00E+00	kg
ES	Gas	Externalised	Biosphere	out	oil	0.00E+00	kg
ES	Gas	Externalised	Biosphere	out	spent nuclear fuel	0.00E+00	kg
ES	Gas	Externalised	Biosphere	out	uranium	0.00E+00	kg
ES	Gas	Externalised	Biosphere	out	waste	9.50E+07	kg
ES	Gas	Externalised	Biosphere	out	water_bio	0.00E+00	l
ES	Gas	Total	Technosphere	in	biofuels	0.00E+00	MJ
ES	Gas	Total	Technosphere	in	biogas	0.00E+00	MJ
ES	Gas	Total	Technosphere	in	coal products	0.00E+00	kg
ES	Gas	Total	Technosphere	in	derived heat	0.00E+00	MJ
ES	Gas	Total	Technosphere	in	electricity	3.13E+08	MJ
ES	Gas	Total	Technosphere	in	human activity	1.71E+08	hrs
ES	Gas	Total	Technosphere	in	manufactured gas	0.00E+00	MJ
ES	Gas	Total	Technosphere	in	nuclear fuel element	0.00E+00	kg
ES	Gas	Total	Technosphere	in	other hydrocarbons	0.00E+00	kg
ES	Gas	Total	Technosphere	in	power capacity	0.00E+00	MW
ES	Gas	Total	Technosphere	in	solid fossil fuels	0.00E+00	kg
ES	Gas	Total	Technosphere	in	total oil products	3.75E+06	MJ
ES	Gas	Total	Technosphere	in	waste	0.00E+00	kg
ES	Gas	Total	Technosphere	in	water_techno	0.00E+00	l
ES	Gas	Total	Biosphere	in	land use	8.93E+01	ha
ES	Gas	Total	Biosphere	in	water_bio	2.28E+09	l
ES	Gas	Total	Biosphere	out	biomass	0.00E+00	kg
ES	Gas	Total	Biosphere	out	coal	0.00E+00	kg
ES	Gas	Total	Biosphere	out	gas	1.33E+10	m3
ES	Gas	Total	Biosphere	out	greenhouse gases	1.56E+09	kg CO2 eq.
ES	Gas	Total	Biosphere	out	lignite	0.00E+00	kg

ES	Gas	Total	Biosphere	out	oil	0.00E+00	kg
ES	Gas	Total	Biosphere	out	spent nuclear fuel	0.00E+00	kg
ES	Gas	Total	Biosphere	out	uranium	0.00E+00	kg
ES	Gas	Total	Biosphere	out	waste	9.50E+07	kg
ES	Gas	Total	Biosphere	out	water_bio	0.00E+00	l
ES	Energy Sector	Local	Technosphere	in	biofuels	0.00E+00	MJ
ES	Energy Sector	Local	Technosphere	in	biogas	1.13E+10	MJ
ES	Energy Sector	Local	Technosphere	in	coal products	0.00E+00	kg
ES	Energy Sector	Local	Technosphere	in	derived heat	0.00E+00	MJ
ES	Energy Sector	Local	Technosphere	in	electricity	6.47E+10	MJ
ES	Energy Sector	Local	Technosphere	in	human activity	5.46E+07	hrs
ES	Energy Sector	Local	Technosphere	in	manufactured gas	2.65E+11	MJ
ES	Energy Sector	Local	Technosphere	in	nuclear fuel element	1.37E+05	kg
ES	Energy Sector	Local	Technosphere	in	other hydrocarbons	0.00E+00	kg
ES	Energy Sector	Local	Technosphere	in	power capacity	2.66E+10	MW
ES	Energy Sector	Local	Technosphere	in	solid fossil fuels	0.00E+00	kg
ES	Energy Sector	Local	Technosphere	in	total oil products	2.96E+11	MJ
ES	Energy Sector	Local	Technosphere	in	waste	3.90E+10	kg
ES	Energy Sector	Local	Technosphere	in	water_techno	2.86E+11	l
ES	Energy Sector	Local	Biosphere	in	land use	1.85E+04	ha
ES	Energy Sector	Local	Biosphere	in	water_bio	2.93E+14	l
ES	Energy Sector	Local	Biosphere	out	biomass	0.00E+00	kg
ES	Energy Sector	Local	Biosphere	out	coal	0.00E+00	kg
ES	Energy Sector	Local	Biosphere	out	gas	0.00E+00	m3
ES	Energy Sector	Local	Biosphere	out	greenhouse gases	1.05E+11	kg CO2 eq.
ES	Energy Sector	Local	Biosphere	out	lignite	1.63E+09	kg
ES	Energy Sector	Local	Biosphere	out	oil	0.00E+00	kg
ES	Energy Sector	Local	Biosphere	out	spent nuclear fuel	1.81E+05	kg
ES	Energy Sector	Local	Biosphere	out	uranium	0.00E+00	kg
ES	Energy Sector	Local	Biosphere	out	waste	0.00E+00	kg
ES	Energy Sector	Local	Biosphere	out	water_bio	2.91E+14	l
ES	Energy Sector	Externalised	Technosphere	in	biofuels	0.00E+00	MJ
ES	Energy Sector	Externalised	Technosphere	in	biogas	1.21E+06	MJ
ES	Energy Sector	Externalised	Technosphere	in	coal products	0.00E+00	kg
ES	Energy Sector	Externalised	Technosphere	in	derived heat	3.90E+08	MJ
ES	Energy Sector	Externalised	Technosphere	in	electricity	3.98E+09	MJ
ES	Energy Sector	Externalised	Technosphere	in	human activity	3.26E+08	hrs
ES	Energy Sector	Externalised	Technosphere	in	manufactured gas	4.60E+10	MJ
ES	Energy Sector	Externalised	Technosphere	in	nuclear fuel element	0.00E+00	kg
ES	Energy Sector	Externalised	Technosphere	in	other hydrocarbons	0.00E+00	kg
ES	Energy Sector	Externalised	Technosphere	in	power capacity	0.00E+00	MW
ES	Energy Sector	Externalised	Technosphere	in	solid fossil fuels	0.00E+00	kg

ES	Energy Sector	Externalised	Technosphere	in	total oil products	3.16E+10	MJ
ES	Energy Sector	Externalised	Technosphere	in	waste	0.00E+00	kg
ES	Energy Sector	Externalised	Technosphere	in	water_techno	1.02E+11	l
ES	Energy Sector	Externalised	Biosphere	in	land use	1.48E+05	ha
ES	Energy Sector	Externalised	Biosphere	in	water_bio	5.10E+10	l
ES	Energy Sector	Externalised	Biosphere	out	biomass	0.00E+00	kg
ES	Energy Sector	Externalised	Biosphere	out	coal	1.63E+10	kg
ES	Energy Sector	Externalised	Biosphere	out	gas	3.17E+10	m3
ES	Energy Sector	Externalised	Biosphere	out	greenhouse gases	3.54E+10	kg CO2 eq.
ES	Energy Sector	Externalised	Biosphere	out	lignite	0.00E+00	kg
ES	Energy Sector	Externalised	Biosphere	out	oil	8.61E+10	kg
ES	Energy Sector	Externalised	Biosphere	out	spent nuclear fuel	0.00E+00	kg
ES	Energy Sector	Externalised	Biosphere	out	uranium	1.29E+05	kg
ES	Energy Sector	Externalised	Biosphere	out	waste	1.44E+08	kg
ES	Energy Sector	Externalised	Biosphere	out	water_bio	7.85E+09	l
ES	Energy Sector	Total	Technosphere	in	biofuels	0.00E+00	MJ
ES	Energy Sector	Total	Technosphere	in	biogas	1.13E+10	MJ
ES	Energy Sector	Total	Technosphere	in	coal products	0.00E+00	kg
ES	Energy Sector	Total	Technosphere	in	derived heat	3.90E+08	MJ
ES	Energy Sector	Total	Technosphere	in	electricity	6.87E+10	MJ
ES	Energy Sector	Total	Technosphere	in	human activity	3.80E+08	hrs
ES	Energy Sector	Total	Technosphere	in	manufactured gas	3.11E+11	MJ
ES	Energy Sector	Total	Technosphere	in	nuclear fuel element	1.37E+05	kg
ES	Energy Sector	Total	Technosphere	in	other hydrocarbons	0.00E+00	kg
ES	Energy Sector	Total	Technosphere	in	power capacity	2.66E+10	MW
ES	Energy Sector	Total	Technosphere	in	solid fossil fuels	0.00E+00	kg
ES	Energy Sector	Total	Technosphere	in	total oil products	3.27E+11	MJ
ES	Energy Sector	Total	Technosphere	in	waste	3.90E+10	kg
ES	Energy Sector	Total	Technosphere	in	water_techno	3.88E+11	l
ES	Energy Sector	Total	Biosphere	in	land use	1.66E+05	ha
ES	Energy Sector	Total	Biosphere	in	water_bio	2.93E+14	l
ES	Energy Sector	Total	Biosphere	out	biomass	0.00E+00	kg
ES	Energy Sector	Total	Biosphere	out	coal	1.63E+10	kg
ES	Energy Sector	Total	Biosphere	out	gas	3.17E+10	m3
ES	Energy Sector	Total	Biosphere	out	greenhouse gases	1.41E+11	kg CO2 eq.
ES	Energy Sector	Total	Biosphere	out	lignite	1.63E+09	kg
ES	Energy Sector	Total	Biosphere	out	oil	8.61E+10	kg
ES	Energy Sector	Total	Biosphere	out	spent nuclear fuel	1.81E+05	kg
ES	Energy Sector	Total	Biosphere	out	uranium	1.29E+05	kg
ES	Energy Sector	Total	Biosphere	out	waste	1.44E+08	kg
ES	Energy Sector	Total	Biosphere	out	water_bio	2.91E+14	l

Table 18. Biosphere and technosphere matrices, Sweden (2018). Energy sector is an aggregation of the sectors electricity, heat, fuels and gas.

Country	Sector	Location	Matrix	Orient.	Label	Value	Unit
SE	Electricity	Local	Technosphere	in	biofuels	0.00E+00	MJ
SE	Electricity	Local	Technosphere	in	biogas	0.00E+00	MJ
SE	Electricity	Local	Technosphere	in	coal products	0.00E+00	kg
SE	Electricity	Local	Technosphere	in	derived heat	0.00E+00	MJ
SE	Electricity	Local	Technosphere	in	electricity	2.22E+10	MJ
SE	Electricity	Local	Technosphere	in	human activity	5.40E+06	hrs
SE	Electricity	Local	Technosphere	in	manufactured gas	0.00E+00	MJ
SE	Electricity	Local	Technosphere	in	nuclear fuel element	1.69E+05	kg
SE	Electricity	Local	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Electricity	Local	Technosphere	in	power capacity	4.73E+10	MW
SE	Electricity	Local	Technosphere	in	solid fossil fuels	0.00E+00	kg
SE	Electricity	Local	Technosphere	in	total oil products	2.54E+07	MJ
SE	Electricity	Local	Technosphere	in	waste	0.00E+00	kg
SE	Electricity	Local	Technosphere	in	water_techno	1.95E+11	l
SE	Electricity	Local	Biosphere	in	land use	4.27E+03	ha
SE	Electricity	Local	Biosphere	in	water_bio	5.09E+14	l
SE	Electricity	Local	Biosphere	out	biomass	0.00E+00	kg
SE	Electricity	Local	Biosphere	out	coal	0.00E+00	kg
SE	Electricity	Local	Biosphere	out	gas	0.00E+00	m3
SE	Electricity	Local	Biosphere	out	greenhouse gases	0.00E+00	kg CO2 eq.
SE	Electricity	Local	Biosphere	out	lignite	0.00E+00	kg
SE	Electricity	Local	Biosphere	out	oil	0.00E+00	kg
SE	Electricity	Local	Biosphere	out	spent nuclear fuel	2.22E+05	kg
SE	Electricity	Local	Biosphere	out	uranium	0.00E+00	kg
SE	Electricity	Local	Biosphere	out	waste	0.00E+00	kg
SE	Electricity	Local	Biosphere	out	water_bio	5.07E+14	l
SE	Electricity	Externalised	Technosphere	in	biofuels	0.00E+00	MJ
SE	Electricity	Externalised	Technosphere	in	biogas	0.00E+00	MJ
SE	Electricity	Externalised	Technosphere	in	coal products	0.00E+00	kg
SE	Electricity	Externalised	Technosphere	in	derived heat	0.00E+00	MJ
SE	Electricity	Externalised	Technosphere	in	electricity	0.00E+00	MJ
SE	Electricity	Externalised	Technosphere	in	human activity	7.61E+04	hrs
SE	Electricity	Externalised	Technosphere	in	manufactured gas	0.00E+00	MJ
SE	Electricity	Externalised	Technosphere	in	nuclear fuel element	0.00E+00	kg
SE	Electricity	Externalised	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Electricity	Externalised	Technosphere	in	power capacity	0.00E+00	MW
SE	Electricity	Externalised	Technosphere	in	solid fossil fuels	0.00E+00	kg
SE	Electricity	Externalised	Technosphere	in	total oil products	1.61E+07	MJ

SE	Electricity	Externalised	Technosphere	in	waste	0.00E+00	kg
SE	Electricity	Externalised	Technosphere	in	water_techno	4.34E+08	l
SE	Electricity	Externalised	Biosphere	in	land use	4.19E+00	ha
SE	Electricity	Externalised	Biosphere	in	water_bio	6.66E+08	l
SE	Electricity	Externalised	Biosphere	out	biomass	0.00E+00	kg
SE	Electricity	Externalised	Biosphere	out	coal	0.00E+00	kg
SE	Electricity	Externalised	Biosphere	out	gas	0.00E+00	m3
SE	Electricity	Externalised	Biosphere	out	greenhouse gases	0.00E+00	kg CO2 eq.
SE	Electricity	Externalised	Biosphere	out	lignite	0.00E+00	kg
SE	Electricity	Externalised	Biosphere	out	oil	0.00E+00	kg
SE	Electricity	Externalised	Biosphere	out	spent nuclear fuel	0.00E+00	kg
SE	Electricity	Externalised	Biosphere	out	uranium	1.59E+05	kg
SE	Electricity	Externalised	Biosphere	out	waste	0.00E+00	kg
SE	Electricity	Externalised	Biosphere	out	water_bio	5.66E+08	l
SE	Electricity	Total	Technosphere	in	biofuels	0.00E+00	MJ
SE	Electricity	Total	Technosphere	in	biogas	0.00E+00	MJ
SE	Electricity	Total	Technosphere	in	coal products	0.00E+00	kg
SE	Electricity	Total	Technosphere	in	derived heat	0.00E+00	MJ
SE	Electricity	Total	Technosphere	in	electricity	2.22E+10	MJ
SE	Electricity	Total	Technosphere	in	human activity	5.48E+06	hrs
SE	Electricity	Total	Technosphere	in	manufactured gas	0.00E+00	MJ
SE	Electricity	Total	Technosphere	in	nuclear fuel element	1.69E+05	kg
SE	Electricity	Total	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Electricity	Total	Technosphere	in	power capacity	4.73E+10	MW
SE	Electricity	Total	Technosphere	in	solid fossil fuels	0.00E+00	kg
SE	Electricity	Total	Technosphere	in	total oil products	4.15E+07	MJ
SE	Electricity	Total	Technosphere	in	waste	0.00E+00	kg
SE	Electricity	Total	Technosphere	in	water_techno	1.95E+11	l
SE	Electricity	Total	Biosphere	in	land use	4.27E+03	ha
SE	Electricity	Total	Biosphere	in	water_bio	5.09E+14	l
SE	Electricity	Total	Biosphere	out	biomass	0.00E+00	kg
SE	Electricity	Total	Biosphere	out	coal	0.00E+00	kg
SE	Electricity	Total	Biosphere	out	gas	0.00E+00	m3
SE	Electricity	Total	Biosphere	out	greenhouse gases	0.00E+00	kg CO2 eq.
SE	Electricity	Total	Biosphere	out	lignite	0.00E+00	kg
SE	Electricity	Total	Biosphere	out	oil	0.00E+00	kg
SE	Electricity	Total	Biosphere	out	spent nuclear fuel	2.22E+05	kg
SE	Electricity	Total	Biosphere	out	uranium	1.59E+05	kg
SE	Electricity	Total	Biosphere	out	waste	0.00E+00	kg
SE	Electricity	Total	Biosphere	out	water_bio	5.07E+14	l
SE	Fuels	Local	Technosphere	in	biofuels	0.00E+00	MJ
SE	Fuels	Local	Technosphere	in	biogas	0.00E+00	MJ

SE	Fuels	Local	Technosphere	in	coal products	0.00E+00	kg
SE	Fuels	Local	Technosphere	in	derived heat	0.00E+00	MJ
SE	Fuels	Local	Technosphere	in	electricity	5.63E+09	MJ
SE	Fuels	Local	Technosphere	in	human activity	5.34E+06	hrs
SE	Fuels	Local	Technosphere	in	manufactured gas	1.24E+11	MJ
SE	Fuels	Local	Technosphere	in	nuclear fuel element	0.00E+00	kg
SE	Fuels	Local	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Fuels	Local	Technosphere	in	power capacity	0.00E+00	MW
SE	Fuels	Local	Technosphere	in	solid fossil fuels	0.00E+00	kg
SE	Fuels	Local	Technosphere	in	total oil products	5.90E+10	MJ
SE	Fuels	Local	Technosphere	in	waste	0.00E+00	kg
SE	Fuels	Local	Technosphere	in	water_techno	2.22E+09	l
SE	Fuels	Local	Biosphere	in	land use	0.00E+00	ha
SE	Fuels	Local	Biosphere	in	water_bio	7.49E+09	l
SE	Fuels	Local	Biosphere	out	biomass	0.00E+00	kg
SE	Fuels	Local	Biosphere	out	coal	0.00E+00	kg
SE	Fuels	Local	Biosphere	out	gas	0.00E+00	m3
SE	Fuels	Local	Biosphere	out	greenhouse gases	1.37E+10	kg CO2 eq.
SE	Fuels	Local	Biosphere	out	lignite	0.00E+00	kg
SE	Fuels	Local	Biosphere	out	oil	0.00E+00	kg
SE	Fuels	Local	Biosphere	out	spent nuclear fuel	0.00E+00	kg
SE	Fuels	Local	Biosphere	out	uranium	0.00E+00	kg
SE	Fuels	Local	Biosphere	out	waste	0.00E+00	kg
SE	Fuels	Local	Biosphere	out	water_bio	3.31E+07	l
SE	Fuels	Externalised	Technosphere	in	biofuels	0.00E+00	MJ
SE	Fuels	Externalised	Technosphere	in	biogas	0.00E+00	MJ
SE	Fuels	Externalised	Technosphere	in	coal products	0.00E+00	kg
SE	Fuels	Externalised	Technosphere	in	derived heat	3.85E+07	MJ
SE	Fuels	Externalised	Technosphere	in	electricity	1.38E+09	MJ
SE	Fuels	Externalised	Technosphere	in	human activity	2.27E+07	hrs
SE	Fuels	Externalised	Technosphere	in	manufactured gas	1.99E+10	MJ
SE	Fuels	Externalised	Technosphere	in	nuclear fuel element	0.00E+00	kg
SE	Fuels	Externalised	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Fuels	Externalised	Technosphere	in	power capacity	0.00E+00	MW
SE	Fuels	Externalised	Technosphere	in	solid fossil fuels	0.00E+00	kg
SE	Fuels	Externalised	Technosphere	in	total oil products	1.34E+10	MJ
SE	Fuels	Externalised	Technosphere	in	waste	0.00E+00	kg
SE	Fuels	Externalised	Technosphere	in	water_techno	3.24E+10	l
SE	Fuels	Externalised	Biosphere	in	land use	2.56E+04	ha
SE	Fuels	Externalised	Biosphere	in	water_bio	1.46E+10	l
SE	Fuels	Externalised	Biosphere	out	biomass	0.00E+00	kg
SE	Fuels	Externalised	Biosphere	out	coal	0.00E+00	kg

SE	Fuels	Externalised	Biosphere	out	gas	3.68E+09	m3
SE	Fuels	Externalised	Biosphere	out	greenhouse gases	1.13E+10	kg CO2 eq.
SE	Fuels	Externalised	Biosphere	out	lignite	0.00E+00	kg
SE	Fuels	Externalised	Biosphere	out	oil	2.75E+10	kg
SE	Fuels	Externalised	Biosphere	out	spent nuclear fuel	0.00E+00	kg
SE	Fuels	Externalised	Biosphere	out	uranium	0.00E+00	kg
SE	Fuels	Externalised	Biosphere	out	waste	0.00E+00	kg
SE	Fuels	Externalised	Biosphere	out	water_bio	3.19E+08	l
SE	Fuels	Total	Technosphere	in	biofuels	0.00E+00	MJ
SE	Fuels	Total	Technosphere	in	biogas	0.00E+00	MJ
SE	Fuels	Total	Technosphere	in	coal products	0.00E+00	kg
SE	Fuels	Total	Technosphere	in	derived heat	3.85E+07	MJ
SE	Fuels	Total	Technosphere	in	electricity	7.01E+09	MJ
SE	Fuels	Total	Technosphere	in	human activity	2.81E+07	hrs
SE	Fuels	Total	Technosphere	in	manufactured gas	1.43E+11	MJ
SE	Fuels	Total	Technosphere	in	nuclear fuel element	0.00E+00	kg
SE	Fuels	Total	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Fuels	Total	Technosphere	in	power capacity	0.00E+00	MW
SE	Fuels	Total	Technosphere	in	solid fossil fuels	0.00E+00	kg
SE	Fuels	Total	Technosphere	in	total oil products	7.24E+10	MJ
SE	Fuels	Total	Technosphere	in	waste	0.00E+00	kg
SE	Fuels	Total	Technosphere	in	water_techno	3.46E+10	l
SE	Fuels	Total	Biosphere	in	land use	2.56E+04	ha
SE	Fuels	Total	Biosphere	in	water_bio	2.20E+10	l
SE	Fuels	Total	Biosphere	out	biomass	0.00E+00	kg
SE	Fuels	Total	Biosphere	out	coal	0.00E+00	kg
SE	Fuels	Total	Biosphere	out	gas	3.68E+09	m3
SE	Fuels	Total	Biosphere	out	greenhouse gases	2.50E+10	kg CO2 eq.
SE	Fuels	Total	Biosphere	out	lignite	0.00E+00	kg
SE	Fuels	Total	Biosphere	out	oil	2.75E+10	kg
SE	Fuels	Total	Biosphere	out	spent nuclear fuel	0.00E+00	kg
SE	Fuels	Total	Biosphere	out	uranium	0.00E+00	kg
SE	Fuels	Total	Biosphere	out	waste	0.00E+00	kg
SE	Fuels	Total	Biosphere	out	water_bio	3.52E+08	l
SE	Fuels	Total	Technosphere	in	biofuels	0.00E+00	MJ
SE	Gas	Local	Technosphere	in	biogas	0.00E+00	MJ
SE	Gas	Local	Technosphere	in	coal products	0.00E+00	MJ
SE	Gas	Local	Technosphere	in	derived heat	0.00E+00	kg
SE	Gas	Local	Technosphere	in	electricity	0.00E+00	MJ
SE	Gas	Local	Technosphere	in	human activity	0.00E+00	MJ
SE	Gas	Local	Technosphere	in	manufactured gas	0.00E+00	hrs

SE	Gas	Local	Technosphere	in	nuclear fuel element	0.00E+00	MJ
SE	Gas	Local	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Gas	Local	Technosphere	in	power capacity	0.00E+00	kg
SE	Gas	Local	Technosphere	in	solid fossil fuels	0.00E+00	MW
SE	Gas	Local	Technosphere	in	total oil products	0.00E+00	kg
SE	Gas	Local	Technosphere	in	waste	0.00E+00	MJ
SE	Gas	Local	Technosphere	in	water_techno	0.00E+00	l
SE	Gas	Local	Biosphere	in	land use	0.00E+00	ha
SE	Gas	Local	Biosphere	in	water_bio	0.00E+00	l
SE	Gas	Local	Biosphere	out	biomass	0.00E+00	kg
SE	Gas	Local	Biosphere	out	coal	0.00E+00	kg
SE	Gas	Local	Biosphere	out	gas	0.00E+00	m3
SE	Gas	Local	Biosphere	out	greenhouse gases	0.00E+00	kg CO2 eq.
SE	Gas	Local	Biosphere	out	lignite	0.00E+00	kg
SE	Gas	Local	Biosphere	out	oil	0.00E+00	kg
SE	Gas	Local	Biosphere	out	spent nuclear fuel	0.00E+00	kg
SE	Gas	Local	Biosphere	out	uranium	0.00E+00	kg
SE	Gas	Local	Biosphere	out	waste	0.00E+00	kg
SE	Gas	Local	Biosphere	out	water_bio	0.00E+00	l
SE	Gas	Externalised	Technosphere	in	biofuels	0.00E+00	MJ
SE	Gas	Externalised	Technosphere	in	biogas	0.00E+00	MJ
SE	Gas	Externalised	Technosphere	in	coal products	0.00E+00	kg
SE	Gas	Externalised	Technosphere	in	derived heat	0.00E+00	MJ
SE	Gas	Externalised	Technosphere	in	electricity	2.06E+07	MJ
SE	Gas	Externalised	Technosphere	in	human activity	1.12E+07	hrs
SE	Gas	Externalised	Technosphere	in	manufactured gas	0.00E+00	MJ
SE	Gas	Externalised	Technosphere	in	nuclear fuel element	0.00E+00	kg
SE	Gas	Externalised	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Gas	Externalised	Technosphere	in	power capacity	0.00E+00	MW
SE	Gas	Externalised	Technosphere	trin	solid fossil fuels	0.00E+00	kg
SE	Gas	Externalised	Technosphere	in	total oil products	2.47E+05	MJ
SE	Gas	Externalised	Technosphere	in	waste	0.00E+00	kg
SE	Gas	Externalised	Technosphere	in	water_techno	0.00E+00	l
SE	Gas	Externalised	Biosphere	in	land use	5.88E+00	ha
SE	Gas	Externalised	Biosphere	in	water_bio	1.50E+08	l
SE	Gas	Externalised	Biosphere	out	biomass	0.00E+00	kg
SE	Gas	Externalised	Biosphere	out	coal	0.00E+00	kg
SE	Gas	Externalised	Biosphere	out	gas	8.77E+08	m3
SE	Gas	Externalised	Biosphere	out	greenhouse gases	1.02E+08	kg CO2 eq.
SE	Gas	Externalised	Biosphere	out	lignite	0.00E+00	kg
SE	Gas	Externalised	Biosphere	out	oil	0.00E+00	kg

SE	Gas	Externalised	Biosphere	out	spent nuclear fuel	0.00E+00	kg
SE	Gas	Externalised	Biosphere	out	uranium	0.00E+00	kg
SE	Gas	Externalised	Biosphere	out	waste	6.24E+06	kg
SE	Gas	Externalised	Biosphere	out	water_bio	0.00E+00	l
SE	Gas	Total	Technosphere	in	biofuels	0.00E+00	MJ
SE	Gas	Total	Technosphere	in	biogas	0.00E+00	MJ
SE	Gas	Total	Technosphere	in	coal products	0.00E+00	kg
SE	Gas	Total	Technosphere	in	derived heat	0.00E+00	MJ
SE	Gas	Total	Technosphere	in	electricity	2.06E+07	MJ
SE	Gas	Total	Technosphere	in	human activity	1.12E+07	hrs
SE	Gas	Total	Technosphere	in	manufactured gas	0.00E+00	MJ
SE	Gas	Total	Technosphere	in	nuclear fuel element	0.00E+00	kg
SE	Gas	Total	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Gas	Total	Technosphere	in	power capacity	0.00E+00	MW
SE	Gas	Total	Technosphere	trin	solid fossil fuels	0.00E+00	kg
SE	Gas	Total	Technosphere	in	total oil products	2.47E+05	MJ
SE	Gas	Total	Technosphere	in	waste	0.00E+00	kg
SE	Gas	Total	Technosphere	in	water_techno	0.00E+00	l
SE	Gas	Total	Biosphere	in	land use	5.88E+00	ha
SE	Gas	Total	Biosphere	in	water_bio	1.50E+08	l
SE	Gas	Total	Biosphere	out	biomass	0.00E+00	kg
SE	Gas	Total	Biosphere	out	coal	0.00E+00	kg
SE	Gas	Total	Biosphere	out	gas	8.77E+08	m3
SE	Gas	Total	Biosphere	out	greenhouse gases	1.02E+08	kg CO2 eq.
SE	Gas	Total	Biosphere	out	lignite	0.00E+00	kg
SE	Gas	Total	Biosphere	out	oil	0.00E+00	kg
SE	Gas	Total	Biosphere	out	spent nuclear fuel	0.00E+00	kg
SE	Gas	Total	Biosphere	out	uranium	0.00E+00	kg
SE	Gas	Total	Biosphere	out	waste	6.24E+06	kg
SE	Gas	Total	Biosphere	out	water_bio	0.00E+00	l
SE	Heat	Local	Technosphere	in	biofuels	1.05E+08	MJ
SE	Heat	Local	Technosphere	in	biogas	5.41E+08	MJ
SE	Heat	Local	Technosphere	in	coal products	0.00E+00	kg
SE	Heat	Local	Technosphere	in	derived heat	0.00E+00	MJ
SE	Heat	Local	Technosphere	in	electricity	1.04E+10	MJ
SE	Heat	Local	Technosphere	in	human activity	1.47E+08	hrs
SE	Heat	Local	Technosphere	in	manufactured gas	1.56E+10	MJ
SE	Heat	Local	Technosphere	in	nuclear fuel element	0.00E+00	kg
SE	Heat	Local	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Heat	Local	Technosphere	in	power capacity	5.25E+03	MW
SE	Heat	Local	Technosphere	in	solid fossil fuels	9.79E+08	kg

SE	Heat	Local	Technosphere	in	total oil products	1.74E+08	MJ
SE	Heat	Local	Technosphere	in	waste	4.48E+09	kg
SE	Heat	Local	Technosphere	in	water_techno	7.86E+09	l
SE	Heat	Local	Biosphere	in	land use	1.46E+02	ha
SE	Heat	Local	Biosphere	in	water_bio	5.43E+11	l
SE	Heat	Local	Biosphere	out	biomass	0.00E+00	kg
SE	Heat	Local	Biosphere	out	coal	0.00E+00	kg
SE	Heat	Local	Biosphere	out	gas	0.00E+00	m3
SE	Heat	Local	Biosphere	out	greenhouse gases	2.06E+10	kg CO2 eq.
SE	Heat	Local	Biosphere	out	lignite	0.00E+00	kg
SE	Heat	Local	Biosphere	out	oil	0.00E+00	kg
SE	Heat	Local	Biosphere	out	spent nuclear fuel	0.00E+00	kg
SE	Heat	Local	Biosphere	out	uranium	0.00E+00	kg
SE	Heat	Local	Biosphere	out	waste	1.46E+09	kg
SE	Heat	Local	Biosphere	out	water_bio	4.52E+11	l
SE	Heat	Externalised	Technosphere	in	biofuels	0.00E+00	MJ
SE	Heat	Externalised	Technosphere	in	biogas	1.83E+05	MJ
SE	Heat	Externalised	Technosphere	in	coal products	0.00E+00	kg
SE	Heat	Externalised	Technosphere	in	derived heat	1.17E+08	MJ
SE	Heat	Externalised	Technosphere	in	electricity	1.82E+08	MJ
SE	Heat	Externalised	Technosphere	in	human activity	5.91E+06	hrs
SE	Heat	Externalised	Technosphere	in	manufactured gas	0.00E+00	MJ
SE	Heat	Externalised	Technosphere	in	nuclear fuel element	0.00E+00	kg
SE	Heat	Externalised	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Heat	Externalised	Technosphere	in	power capacity	0.00E+00	MW
SE	Heat	Externalised	Technosphere	in	solid fossil fuels	0.00E+00	kg
SE	Heat	Externalised	Technosphere	in	total oil products	6.34E+06	MJ
SE	Heat	Externalised	Technosphere	in	waste	0.00E+00	kg
SE	Heat	Externalised	Technosphere	in	water_techno	7.98E+08	l
SE	Heat	Externalised	Biosphere	in	land use	2.19E+04	ha
SE	Heat	Externalised	Biosphere	in	water_bio	1.72E+09	l
SE	Heat	Externalised	Biosphere	out	biomass	0.00E+00	kg
SE	Heat	Externalised	Biosphere	out	coal	3.03E+09	kg
SE	Heat	Externalised	Biosphere	out	gas	2.63E+08	m3
SE	Heat	Externalised	Biosphere	out	greenhouse gases	4.22E+08	kg CO2 eq.
SE	Heat	Externalised	Biosphere	out	lignite	0.00E+00	kg
SE	Heat	Externalised	Biosphere	out	oil	0.00E+00	kg
SE	Heat	Externalised	Biosphere	out	spent nuclear fuel	0.00E+00	kg
SE	Heat	Externalised	Biosphere	out	uranium	0.00E+00	kg
SE	Heat	Externalised	Biosphere	out	waste	1.87E+06	kg
SE	Heat	Externalised	Biosphere	out	water_bio	2.37E+09	l
SE	Heat	Total	Technosphere	in	biofuels	1.05E+08	MJ

SE	Heat	Total	Technosphere	in	biogas	5.42E+08	MJ
SE	Heat	Total	Technosphere	in	coal products	0.00E+00	kg
SE	Heat	Total	Technosphere	in	derived heat	1.17E+08	MJ
SE	Heat	Total	Technosphere	in	electricity	1.06E+10	MJ
SE	Heat	Total	Technosphere	in	human activity	1.53E+08	hrs
SE	Heat	Total	Technosphere	in	manufactured gas	1.56E+10	MJ
SE	Heat	Total	Technosphere	in	nuclear fuel element	0.00E+00	kg
SE	Heat	Total	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Heat	Total	Technosphere	in	power capacity	5.25E+03	MW
SE	Heat	Total	Technosphere	in	solid fossil fuels	9.79E+08	kg
SE	Heat	Total	Technosphere	in	total oil products	1.80E+08	MJ
SE	Heat	Total	Technosphere	in	waste	4.48E+09	kg
SE	Heat	Total	Technosphere	in	water_techno	8.65E+09	l
SE	Heat	Total	Biosphere	in	land use	2.20E+04	ha
SE	Heat	Total	Biosphere	in	water_bio	5.45E+11	l
SE	Heat	Total	Biosphere	out	biomass	0.00E+00	kg
SE	Heat	Total	Biosphere	out	coal	3.03E+09	kg
SE	Heat	Total	Biosphere	out	gas	2.63E+08	m3
SE	Heat	Total	Biosphere	out	greenhouse gases	2.10E+10	kg CO2 eq.
SE	Heat	Total	Biosphere	out	lignite	0.00E+00	kg
SE	Heat	Total	Biosphere	out	oil	0.00E+00	kg
SE	Heat	Total	Biosphere	out	spent nuclear fuel	0.00E+00	kg
SE	Heat	Total	Biosphere	out	uranium	0.00E+00	kg
SE	Heat	Total	Biosphere	out	waste	1.46E+09	kg
SE	Heat	Total	Biosphere	out	water_bio	4.54E+11	l
SE	Energy Sector	Local	Technosphere	in	biofuels	1.05E+08	MJ
SE	Energy Sector	Local	Technosphere	in	biogas	5.41E+08	MJ
SE	Energy Sector	Local	Technosphere	in	coal products	0.00E+00	kg
SE	Energy Sector	Local	Technosphere	in	derived heat	0.00E+00	MJ
SE	Energy Sector	Local	Technosphere	in	electricity	3.82E+10	MJ
SE	Energy Sector	Local	Technosphere	in	human activity	1.58E+08	hrs
SE	Energy Sector	Local	Technosphere	in	manufactured gas	1.39E+11	MJ
SE	Energy Sector	Local	Technosphere	in	nuclear fuel element	1.69E+05	kg
SE	Energy Sector	Local	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Energy Sector	Local	Technosphere	in	power capacity	4.73E+10	MW
SE	Energy Sector	Local	Technosphere	in	solid fossil fuels	9.79E+08	kg
SE	Energy Sector	Local	Technosphere	in	total oil products	5.92E+10	MJ
SE	Energy Sector	Local	Technosphere	in	waste	4.48E+09	kg
SE	Energy Sector	Local	Technosphere	in	water_techno	2.05E+11	l
SE	Energy Sector	Local	Biosphere	in	land use	4.41E+03	ha
SE	Energy Sector	Local	Biosphere	in	water_bio	5.10E+14	l
SE	Energy Sector	Local	Biosphere	out	biomass	0.00E+00	kg

SE	Energy Sector	Local	Biosphere	out	coal	0.00E+00	kg
SE	Energy Sector	Local	Biosphere	out	gas	0.00E+00	m3
SE	Energy Sector	Local	Biosphere	out	greenhouse gases	3.43E+10	kg CO2 eq.
SE	Energy Sector	Local	Biosphere	out	lignite	0.00E+00	kg
SE	Energy Sector	Local	Biosphere	out	oil	0.00E+00	kg
SE	Energy Sector	Local	Biosphere	out	spent nuclear fuel	2.22E+05	kg
SE	Energy Sector	Local	Biosphere	out	uranium	0.00E+00	kg
SE	Energy Sector	Local	Biosphere	out	waste	1.46E+09	kg
SE	Energy Sector	Local	Biosphere	out	water_bio	5.07E+14	l
SE	Energy Sector	Externalised	Technosphere	in	biofuels	0.00E+00	MJ
SE	Energy Sector	Externalised	Technosphere	in	biogas	1.83E+05	MJ
SE	Energy Sector	Externalised	Technosphere	in	coal products	0.00E+00	kg
SE	Energy Sector	Externalised	Technosphere	in	derived heat	1.76E+08	MJ
SE	Energy Sector	Externalised	Technosphere	in	electricity	1.57E+09	MJ
SE	Energy Sector	Externalised	Technosphere	in	human activity	2.87E+07	hrs
SE	Energy Sector	Externalised	Technosphere	in	manufactured gas	1.99E+10	MJ
SE	Energy Sector	Externalised	Technosphere	in	nuclear fuel element	0.00E+00	kg
SE	Energy Sector	Externalised	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Energy Sector	Externalised	Technosphere	in	power capacity	0.00E+00	MW
SE	Energy Sector	Externalised	Technosphere	in	solid fossil fuels	2.47E+05	kg
SE	Energy Sector	Externalised	Technosphere	in	total oil products	1.34E+10	MJ
SE	Energy Sector	Externalised	Technosphere	in	waste	0.00E+00	kg
SE	Energy Sector	Externalised	Technosphere	in	water_techno	3.36E+10	l
SE	Energy Sector	Externalised	Biosphere	in	land use	1.50E+08	ha
SE	Energy Sector	Externalised	Biosphere	in	water_bio	1.69E+10	l
SE	Energy Sector	Externalised	Biosphere	out	biomass	0.00E+00	kg
SE	Energy Sector	Externalised	Biosphere	out	coal	3.91E+09	kg
SE	Energy Sector	Externalised	Biosphere	out	gas	4.04E+09	m3
SE	Energy Sector	Externalised	Biosphere	out	greenhouse gases	1.17E+10	kg CO2 eq.
SE	Energy Sector	Externalised	Biosphere	out	lignite	0.00E+00	kg
SE	Energy Sector	Externalised	Biosphere	out	oil	2.75E+10	kg
SE	Energy Sector	Externalised	Biosphere	out	spent nuclear fuel	0.00E+00	kg
SE	Energy Sector	Externalised	Biosphere	out	uranium	6.40E+06	kg
SE	Energy Sector	Externalised	Biosphere	out	waste	1.87E+06	kg
SE	Energy Sector	Externalised	Biosphere	out	water_bio	3.25E+09	l
SE	Energy Sector	Total	Technosphere	in	biofuels	1.05E+08	MJ
SE	Energy Sector	Total	Technosphere	in	biogas	5.42E+08	MJ
SE	Energy Sector	Total	Technosphere	in	coal products	0.00E+00	kg
SE	Energy Sector	Total	Technosphere	in	derived heat	1.55E+08	MJ
SE	Energy Sector	Total	Technosphere	in	electricity	3.98E+10	MJ
SE	Energy Sector	Total	Technosphere	in	human activity	1.98E+08	hrs
SE	Energy Sector	Total	Technosphere	in	manufactured gas	1.59E+11	MJ

SE	Energy Sector	Total	Technosphere	in	nuclear fuel element	1.69E+05	kg
SE	Energy Sector	Total	Technosphere	in	other hydrocarbons	0.00E+00	kg
SE	Energy Sector	Total	Technosphere	in	power capacity	4.73E+10	MW
SE	Energy Sector	Total	Technosphere	in	solid fossil fuels	9.79E+08	kg
SE	Energy Sector	Total	Technosphere	in	total oil products	7.26E+10	MJ
SE	Energy Sector	Total	Technosphere	in	waste	4.48E+09	kg
SE	Energy Sector	Total	Technosphere	in	water_techno	2.38E+11	l
SE	Energy Sector	Total	Biosphere	in	land use	5.19E+04	ha
SE	Energy Sector	Total	Biosphere	in	water_bio	5.10E+14	l
SE	Energy Sector	Total	Biosphere	out	biomass	0.00E+00	kg
SE	Energy Sector	Total	Biosphere	out	coal	3.03E+09	kg
SE	Energy Sector	Total	Biosphere	out	gas	4.82E+09	m3
SE	Energy Sector	Total	Biosphere	out	greenhouse gases	4.61E+10	kg CO2 eq.
SE	Energy Sector	Total	Biosphere	out	lignite	0.00E+00	kg
SE	Energy Sector	Total	Biosphere	out	oil	2.75E+10	kg
SE	Energy Sector	Total	Biosphere	out	spent nuclear fuel	2.22E+05	kg
SE	Energy Sector	Total	Biosphere	out	uranium	1.59E+05	kg
SE	Energy Sector	Total	Biosphere	out	waste	1.47E+09	kg
SE	Energy Sector	Total	Biosphere	out	water_bio	5.07E+14	l

Table 19. Biosphere and technosphere matrices, EU (2018). Energy sector is an aggregation of the sectors electricity, heat, fuels and gas.

Country	Sector	Location	Matrix	Orient.	Code	Value	Unit
EU	Electricity	Local	Technosphere	in	biofuels	1.60E+10	MJ
EU	Electricity	Local	Technosphere	in	biogas	8.21E+11	MJ
EU	Electricity	Local	Technosphere	in	coal products	1.63E+09	kg
EU	Electricity	Local	Technosphere	in	derived heat	1.56E+07	MJ
EU	Electricity	Local	Technosphere	in	electricity	1.09E+12	MJ
EU	Electricity	Local	Technosphere	in	human activity	1.71E+09	hrs
EU	Electricity	Local	Technosphere	in	manufactured gas	5.53E+11	MJ
EU	Electricity	Local	Technosphere	in	nuclear fuel element	2.01E+06	kg
EU	Electricity	Local	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Electricity	Local	Technosphere	in	power capacity	2.87E+11	MW
EU	Electricity	Local	Technosphere	in	solid fossil fuels	6.42E+09	kg
EU	Electricity	Local	Technosphere	in	total oil products	2.22E+11	MJ
EU	Electricity	Local	Technosphere	in	waste	7.60E+10	kg
EU	Electricity	Local	Technosphere	in	water_techno	4.48E+12	l
EU	Electricity	Local	Biosphere	in	land use	2.31E+05	ha

EU	Electricity	Local	Biosphere	in	water_bio	3.19E+15	l
EU	Electricity	Local	Biosphere	out	biomass	0.00E+00	kg
EU	Electricity	Local	Biosphere	out	coal	1.48E+08	kg
EU	Electricity	Local	Biosphere	out	gas	3.47E+10	m3
EU	Electricity	Local	Biosphere	out	greenhouse gases	1.35E+12	kg CO2 eq.
EU	Electricity	Local	Biosphere	out	lignite	0.00E+00	kg
EU	Electricity	Local	Biosphere	out	oil	0.00E+00	kg
EU	Electricity	Local	Biosphere	out	spent nuclear fuel	2.65E+06	kg
EU	Electricity	Local	Biosphere	out	uranium	0.00E+00	kg
EU	Electricity	Local	Biosphere	out	waste	2.07E+08	kg
EU	Electricity	Local	Biosphere	out	water_bio	3.18E+15	l
EU	Electricity	Externalised	Technosphere	in	biofuels	0.00E+00	MJ
EU	Electricity	Externalised	Technosphere	in	biogas	2.61E+07	MJ
EU	Electricity	Externalised	Technosphere	in	coal products	0.00E+00	kg
EU	Electricity	Externalised	Technosphere	in	derived heat	8.19E+09	MJ
EU	Electricity	Externalised	Technosphere	in	electricity	1.30E+10	MJ
EU	Electricity	Externalised	Technosphere	in	human activity	1.85E+09	hrs
EU	Electricity	Externalised	Technosphere	in	manufactured gas	0.00E+00	MJ
EU	Electricity	Externalised	Technosphere	in	nuclear fuel element	0.00E+00	kg
EU	Electricity	Externalised	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Electricity	Externalised	Technosphere	in	power capacity	0.00E+00	MW
EU	Electricity	Externalised	Technosphere	in	solid fossil fuels	0.00E+00	kg
EU	Electricity	Externalised	Technosphere	in	total oil products	9.88E+08	MJ
EU	Electricity	Externalised	Technosphere	in	waste	0.00E+00	kg
EU	Electricity	Externalised	Technosphere	in	water_techno	4.96E+10	l
EU	Electricity	Externalised	Biosphere	in	land use	1.46E+06	ha
EU	Electricity	Externalised	Biosphere	in	water_bio	1.37E+11	l
EU	Electricity	Externalised	Biosphere	out	biomass	0.00E+00	kg
EU	Electricity	Externalised	Biosphere	out	coal	3.51E+11	kg
EU	Electricity	Externalised	Biosphere	out	gas	1.31E+11	m3
EU	Electricity	Externalised	Biosphere	out	greenhouse gases	3.97E+10	kg CO2 eq.
EU	Electricity	Externalised	Biosphere	out	lignite	0.00E+00	kg
EU	Electricity	Externalised	Biosphere	out	oil	0.00E+00	kg
EU	Electricity	Externalised	Biosphere	out	spent nuclear fuel	0.00E+00	kg
EU	Electricity	Externalised	Biosphere	out	uranium	3.89E+06	kg
EU	Electricity	Externalised	Biosphere	out	waste	1.41E+09	kg
EU	Electricity	Externalised	Biosphere	out	water_bio	1.60E+11	l
EU	Electricity	Total	Technosphere	in	biofuels	1.60E+10	MJ
EU	Electricity	Total	Technosphere	in	biogas	8.21E+11	MJ
EU	Electricity	Total	Technosphere	in	coal products	1.63E+09	kg
EU	Electricity	Total	Technosphere	in	derived heat	8.21E+09	MJ
EU	Electricity	Total	Technosphere	in	electricity	1.11E+12	MJ

EU	Electricity	Total	Technosphere	in	human activity	3.56E+09	hrs
EU	Electricity	Total	Technosphere	in	manufactured gas	5.53E+11	MJ
EU	Electricity	Total	Technosphere	in	nuclear fuel element	2.01E+06	kg
EU	Electricity	Total	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Electricity	Total	Technosphere	in	power capacity	2.87E+11	MW
EU	Electricity	Total	Technosphere	in	solid fossil fuels	6.42E+09	kg
EU	Electricity	Total	Technosphere	in	total oil products	2.23E+11	MJ
EU	Electricity	Total	Technosphere	in	waste	7.60E+10	kg
EU	Electricity	Total	Technosphere	in	water_techno	4.53E+12	l
EU	Electricity	Total	Biosphere	in	land use	1.69E+06	ha
EU	Electricity	Total	Biosphere	in	water_bio	3.19E+15	l
EU	Electricity	Total	Biosphere	out	biomass	0.00E+00	kg
EU	Electricity	Total	Biosphere	out	coal	3.51E+11	kg
EU	Electricity	Total	Biosphere	out	gas	1.66E+11	m3
EU	Electricity	Total	Biosphere	out	greenhouse gases	1.39E+12	kg CO2 eq.
EU	Electricity	Total	Biosphere	out	lignite	0.00E+00	kg
EU	Electricity	Total	Biosphere	out	oil	0.00E+00	kg
EU	Electricity	Total	Biosphere	out	spent nuclear fuel	2.65E+06	kg
EU	Electricity	Total	Biosphere	out	uranium	3.89E+06	kg
EU	Electricity	Total	Biosphere	out	waste	1.62E+09	kg
EU	Electricity	Total	Biosphere	out	water_bio	3.18E+15	l
EU	Fuels	Local	Technosphere	in	biofuels	0.00E+00	MJ
EU	Fuels	Local	Technosphere	in	biogas	0.00E+00	MJ
EU	Fuels	Local	Technosphere	in	coal products	0.00E+00	kg
EU	Fuels	Local	Technosphere	in	derived heat	0.00E+00	MJ
EU	Fuels	Local	Technosphere	in	electricity	1.26E+11	MJ
EU	Fuels	Local	Technosphere	in	human activity	2.00E+08	hrs
EU	Fuels	Local	Technosphere	in	manufactured gas	2.44E+12	MJ
EU	Fuels	Local	Technosphere	in	nuclear fuel element	0.00E+00	kg
EU	Fuels	Local	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Fuels	Local	Technosphere	in	power capacity	0.00E+00	MW
EU	Fuels	Local	Technosphere	in	solid fossil fuels	0.00E+00	kg
EU	Fuels	Local	Technosphere	in	total oil products	1.47E+12	MJ
EU	Fuels	Local	Technosphere	in	waste	0.00E+00	kg
EU	Fuels	Local	Technosphere	in	water_techno	9.43E+10	l
EU	Fuels	Local	Biosphere	in	land use	0.00E+00	ha
EU	Fuels	Local	Biosphere	in	water_bio	2.21E+11	l
EU	Fuels	Local	Biosphere	out	biomass	0.00E+00	kg
EU	Fuels	Local	Biosphere	out	coal	0.00E+00	kg
EU	Fuels	Local	Biosphere	out	gas	1.01E+10	m3
EU	Fuels	Local	Biosphere	out	greenhouse gases	3.11E+11	kg CO2 eq.
EU	Fuels	Local	Biosphere	out	lignite	0.00E+00	kg

EU	Fuels	Local	Biosphere	out	oil	6.88E+10	kg
EU	Fuels	Local	Biosphere	out	spent nuclear fuel	0.00E+00	kg
EU	Fuels	Local	Biosphere	out	uranium	0.00E+00	kg
EU	Fuels	Local	Biosphere	out	waste	0.00E+00	kg
EU	Fuels	Local	Biosphere	out	water_bio	1.84E+09	l
EU	Fuels	Externalised	Technosphere	in	biofuels	0.00E+00	MJ
EU	Fuels	Externalised	Technosphere	in	biogas	0.00E+00	MJ
EU	Fuels	Externalised	Technosphere	in	coal products	0.00E+00	kg
EU	Fuels	Externalised	Technosphere	in	derived heat	0.00E+00	MJ
EU	Fuels	Externalised	Technosphere	in	electricity	4.56E+10	MJ
EU	Fuels	Externalised	Technosphere	in	human activity	6.29E+08	hrs
EU	Fuels	Externalised	Technosphere	in	manufactured gas	7.50E+11	MJ
EU	Fuels	Externalised	Technosphere	in	nuclear fuel element	0.00E+00	kg
EU	Fuels	Externalised	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Fuels	Externalised	Technosphere	in	power capacity	0.00E+00	MW
EU	Fuels	Externalised	Technosphere	in	solid fossil fuels	0.00E+00	kg
EU	Fuels	Externalised	Technosphere	in	total oil products	5.00E+11	MJ
EU	Fuels	Externalised	Technosphere	in	waste	0.00E+00	kg
EU	Fuels	Externalised	Technosphere	in	water_techno	1.06E+12	l
EU	Fuels	Externalised	Biosphere	in	land use	8.42E+05	ha
EU	Fuels	Externalised	Biosphere	in	water_bio	4.80E+11	l
EU	Fuels	Externalised	Biosphere	out	biomass	0.00E+00	kg
EU	Fuels	Externalised	Biosphere	out	coal	0.00E+00	kg
EU	Fuels	Externalised	Biosphere	out	gas	1.21E+11	m3
EU	Fuels	Externalised	Biosphere	out	greenhouse gases	3.67E+11	kg CO2 eq.
EU	Fuels	Externalised	Biosphere	out	lignite	0.00E+00	kg
EU	Fuels	Externalised	Biosphere	out	oil	9.15E+11	kg
EU	Fuels	Externalised	Biosphere	out	spent nuclear fuel	0.00E+00	kg
EU	Fuels	Externalised	Biosphere	out	uranium	0.00E+00	kg
EU	Fuels	Externalised	Biosphere	out	waste	0.00E+00	kg
EU	Fuels	Externalised	Biosphere	out	water_bio	1.11E+09	l
EU	Fuels	Total	Technosphere	in	biofuels	0.00E+00	MJ
EU	Fuels	Total	Technosphere	in	biogas	0.00E+00	MJ
EU	Fuels	Total	Technosphere	in	coal products	0.00E+00	kg
EU	Fuels	Total	Technosphere	in	derived heat	0.00E+00	MJ
EU	Fuels	Total	Technosphere	in	electricity	1.71E+11	MJ
EU	Fuels	Total	Technosphere	in	human activity	8.29E+08	hrs
EU	Fuels	Total	Technosphere	in	manufactured gas	3.19E+12	MJ
EU	Fuels	Total	Technosphere	in	nuclear fuel element	0.00E+00	kg
EU	Fuels	Total	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Fuels	Total	Technosphere	in	power capacity	0.00E+00	MW
EU	Fuels	Total	Technosphere	in	solid fossil fuels	0.00E+00	kg

EU	Fuels	Total	Technosphere	in	total oil products	1.97E+12	MJ
EU	Fuels	Total	Technosphere	in	waste	0.00E+00	kg
EU	Fuels	Total	Technosphere	in	water_techno	1.16E+12	l
EU	Fuels	Total	Biosphere	in	land use	8.42E+05	ha
EU	Fuels	Total	Biosphere	in	water_bio	7.01E+11	l
EU	Fuels	Total	Biosphere	out	biomass	0.00E+00	kg
EU	Fuels	Total	Biosphere	out	coal	0.00E+00	kg
EU	Fuels	Total	Biosphere	out	gas	1.31E+11	m3
EU	Fuels	Total	Biosphere	out	greenhouse gases	6.78E+11	kg CO2 eq.
EU	Fuels	Total	Biosphere	out	lignite	0.00E+00	kg
EU	Fuels	Total	Biosphere	out	oil	9.83E+11	kg
EU	Fuels	Total	Biosphere	out	spent nuclear fuel	0.00E+00	kg
EU	Fuels	Total	Biosphere	out	uranium	0.00E+00	kg
EU	Fuels	Total	Biosphere	out	waste	0.00E+00	kg
EU	Fuels	Total	Biosphere	out	water_bio	2.95E+09	l
EU	Gas	Local	Technosphere	in	biofuels	0.00E+00	MJ
EU	Gas	Local	Technosphere	in	biogas	0.00E+00	MJ
EU	Gas	Local	Technosphere	in	coal products	0.00E+00	kg
EU	Gas	Local	Technosphere	in	derived heat	0.00E+00	MJ
EU	Gas	Local	Technosphere	in	electricity	0.00E+00	MJ
EU	Gas	Local	Technosphere	in	human activity	1.06E+09	hrs
EU	Gas	Local	Technosphere	in	manufactured gas	0.00E+00	MJ
EU	Gas	Local	Technosphere	in	nuclear fuel element	0.00E+00	kg
EU	Gas	Local	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Gas	Local	Technosphere	in	power capacity	0.00E+00	MW
EU	Gas	Local	Technosphere	in	solid fossil fuels	0.00E+00	kg
EU	Gas	Local	Technosphere	in	total oil products	1.94E+07	MJ
EU	Gas	Local	Technosphere	trin	waste	0.00E+00	kg
EU	Gas	Local	Technosphere	in	water_techno	0.00E+00	l
EU	Gas	Local	Biosphere	in	land use	5.97E+02	ha
EU	Gas	Local	Biosphere	in	water_bio	1.52E+10	l
EU	Gas	Local	Biosphere	out	biomass	0.00E+00	kg
EU	Gas	Local	Biosphere	out	coal	0.00E+00	kg
EU	Gas	Local	Biosphere	out	gas	8.25E+10	m3
EU	Gas	Local	Biosphere	out	greenhouse gases	9.81E+09	kg CO2 eq.
EU	Gas	Local	Biosphere	out	lignite	0.00E+00	kg
EU	Gas	Local	Biosphere	out	oil	0.00E+00	kg
EU	Gas	Local	Biosphere	out	spent nuclear fuel	0.00E+00	kg
EU	Gas	Local	Biosphere	out	uranium	0.00E+00	kg
EU	Gas	Local	Biosphere	out	waste	4.92E+08	kg
EU	Gas	Local	Biosphere	out	water_bio	0.00E+00	l
EU	Gas	Externalised	Technosphere	in	biofuels	0.00E+00	MJ

EU	Gas	Externalised	Technosphere	in	biogas	0.00E+00	MJ
EU	Gas	Externalised	Technosphere	in	coal products	0.00E+00	kg
EU	Gas	Externalised	Technosphere	in	derived heat	0.00E+00	MJ
EU	Gas	Externalised	Technosphere	in	electricity	5.46E+09	MJ
EU	Gas	Externalised	Technosphere	in	human activity	3.99E+09	hrs
EU	Gas	Externalised	Technosphere	in	manufactured gas	0.00E+00	MJ
EU	Gas	Externalised	Technosphere	in	nuclear fuel element	0.00E+00	kg
EU	Gas	Externalised	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Gas	Externalised	Technosphere	in	power capacity	0.00E+00	MW
EU	Gas	Externalised	Technosphere	in	solid fossil fuels	0.00E+00	kg
EU	Gas	Externalised	Technosphere	in	total oil products	1.33E+08	MJ
EU	Gas	Externalised	Technosphere	in	waste	0.00E+00	kg
EU	Gas	Externalised	Technosphere	in	water_techno	0.00E+00	l
EU	Gas	Externalised	Biosphere	in	land use	1.56E+03	ha
EU	Gas	Externalised	Biosphere	in	water_bio	3.98E+10	l
EU	Gas	Externalised	Biosphere	out	biomass	0.00E+00	kg
EU	Gas	Externalised	Biosphere	out	coal	0.00E+00	kg
EU	Gas	Externalised	Biosphere	out	gas	3.12E+11	m3
EU	Gas	Externalised	Biosphere	out	greenhouse gases	3.43E+10	kg CO2 eq.
EU	Gas	Externalised	Biosphere	out	lignite	0.00E+00	kg
EU	Gas	Externalised	Biosphere	out	oil	0.00E+00	kg
EU	Gas	Externalised	Biosphere	out	spent nuclear fuel	0.00E+00	kg
EU	Gas	Externalised	Biosphere	out	uranium	0.00E+00	kg
EU	Gas	Externalised	Biosphere	out	waste	3.37E+09	kg
EU	Gas	Externalised	Biosphere	out	water_bio	0.00E+00	l
EU	Gas	Total	Technosphere	in	biofuels	0.00E+00	MJ
EU	Gas	Total	Technosphere	in	biogas	0.00E+00	MJ
EU	Gas	Total	Technosphere	in	coal products	0.00E+00	kg
EU	Gas	Total	Technosphere	in	derived heat	0.00E+00	MJ
EU	Gas	Total	Technosphere	in	electricity	5.46E+09	MJ
EU	Gas	Total	Technosphere	in	human activity	5.05E+09	hrs
EU	Gas	Total	Technosphere	in	manufactured gas	0.00E+00	MJ
EU	Gas	Total	Technosphere	in	nuclear fuel element	0.00E+00	kg
EU	Gas	Total	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Gas	Total	Technosphere	in	power capacity	0.00E+00	MW
EU	Gas	Total	Technosphere	in	solid fossil fuels	0.00E+00	kg
EU	Gas	Total	Technosphere	in	total oil products	1.53E+08	MJ
EU	Gas	Total	Technosphere	in	waste	0.00E+00	kg
EU	Gas	Total	Technosphere	in	water_techno	0.00E+00	l
EU	Gas	Total	Biosphere	in	land use	2.16E+03	ha
EU	Gas	Total	Biosphere	in	water_bio	5.50E+10	l
EU	Gas	Total	Biosphere	out	biomass	0.00E+00	kg

EU	Gas	Total	Biosphere	out	coal	0.00E+00	kg
EU	Gas	Total	Biosphere	out	gas	3.95E+11	m3
EU	Gas	Total	Biosphere	out	greenhouse gases	4.41E+10	kg CO2 eq.
EU	Gas	Total	Biosphere	out	lignite	0.00E+00	kg
EU	Gas	Total	Biosphere	out	oil	0.00E+00	kg
EU	Gas	Total	Biosphere	out	spent nuclear fuel	0.00E+00	kg
EU	Gas	Total	Biosphere	out	uranium	0.00E+00	kg
EU	Gas	Total	Biosphere	out	waste	3.86E+09	kg
EU	Gas	Total	Biosphere	out	water_bio	0.00E+00	l
EU	Heat	Local	Technosphere	in	biofuels	3.71E+09	MJ
EU	Heat	Local	Technosphere	in	biogas	2.09E+09	MJ
EU	Heat	Local	Technosphere	in	coal products	0.00E+00	kg
EU	Heat	Local	Technosphere	in	derived heat	8.15E+10	MJ
EU	Heat	Local	Technosphere	in	electricity	3.47E+10	MJ
EU	Heat	Local	Technosphere	in	human activity	1.03E+09	hrs
EU	Heat	Local	Technosphere	in	manufactured gas	6.87E+09	MJ
EU	Heat	Local	Technosphere	in	nuclear fuel element	0.00E+00	kg
EU	Heat	Local	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Heat	Local	Technosphere	in	power capacity	4.46E+03	MW
EU	Heat	Local	Technosphere	in	solid fossil fuels	1.38E+09	kg
EU	Heat	Local	Technosphere	in	total oil products	5.23E+08	MJ
EU	Heat	Local	Technosphere	in	waste	0.00E+00	kg
EU	Heat	Local	Technosphere	in	water_techno	9.04E+09	l
EU	Heat	Local	Biosphere	in	land use	6.19E+02	ha
EU	Heat	Local	Biosphere	in	water_bio	6.71E+11	l
EU	Heat	Local	Biosphere	out	biomass	0.00E+00	kg
EU	Heat	Local	Biosphere	out	coal	0.00E+00	kg
EU	Heat	Local	Biosphere	out	gas	2.39E+10	m3
EU	Heat	Local	Biosphere	out	greenhouse gases	5.60E+10	kg CO2 eq.
EU	Heat	Local	Biosphere	out	lignite	0.00E+00	kg
EU	Heat	Local	Biosphere	out	oil	0.00E+00	kg
EU	Heat	Local	Biosphere	out	spent nuclear fuel	0.00E+00	kg
EU	Heat	Local	Biosphere	out	uranium	0.00E+00	kg
EU	Heat	Local	Biosphere	out	waste	5.30E+08	kg
EU	Heat	Local	Biosphere	out	water_bio	5.30E+11	l
EU	Heat	Externalised	Technosphere	in	biofuels	0.00E+00	MJ
EU	Heat	Externalised	Technosphere	in	biogas	0.00E+00	MJ
EU	Heat	Externalised	Technosphere	in	coal products	0.00E+00	kg
EU	Heat	Externalised	Technosphere	in	derived heat	0.00E+00	MJ
EU	Heat	Externalised	Technosphere	in	electricity	1.58E+09	MJ
EU	Heat	Externalised	Technosphere	in	human activity	1.15E+09	hrs
EU	Heat	Externalised	Technosphere	in	manufactured gas	0.00E+00	MJ

EU	Heat	Externalised	Technosphere	in	nuclear fuel element	0.00E+00	kg
EU	Heat	Externalised	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Heat	Externalised	Technosphere	in	power capacity	0.00E+00	MW
EU	Heat	Externalised	Technosphere	in	solid fossil fuels	0.00E+00	kg
EU	Heat	Externalised	Technosphere	in	total oil products	3.85E+07	MJ
EU	Heat	Externalised	Technosphere	in	waste	0.00E+00	kg
EU	Heat	Externalised	Technosphere	in	water_techno	0.00E+00	l
EU	Heat	Externalised	Biosphere	in	land use	4.51E+02	ha
EU	Heat	Externalised	Biosphere	in	water_bio	1.15E+10	l
EU	Heat	Externalised	Biosphere	out	biomass	0.00E+00	kg
EU	Heat	Externalised	Biosphere	out	coal	0.00E+00	kg
EU	Heat	Externalised	Biosphere	out	gas	9.02E+10	m3
EU	Heat	Externalised	Biosphere	out	greenhouse gases	9.92E+09	kg CO2 eq.
EU	Heat	Externalised	Biosphere	out	lignite	0.00E+00	kg
EU	Heat	Externalised	Biosphere	out	oil	0.00E+00	kg
EU	Heat	Externalised	Biosphere	out	spent nuclear fuel	0.00E+00	kg
EU	Heat	Externalised	Biosphere	out	uranium	0.00E+00	kg
EU	Heat	Externalised	Biosphere	out	waste	9.74E+08	kg
EU	Heat	Externalised	Biosphere	out	water_bio	0.00E+00	l
EU	Heat	Total	Technosphere	in	biofuels	3.71E+09	MJ
EU	Heat	Total	Technosphere	in	biogas	2.09E+09	MJ
EU	Heat	Total	Technosphere	in	coal products	0.00E+00	kg
EU	Heat	Total	Technosphere	in	derived heat	8.15E+10	MJ
EU	Heat	Total	Technosphere	in	electricity	3.63E+10	MJ
EU	Heat	Total	Technosphere	in	human activity	2.18E+09	hrs
EU	Heat	Total	Technosphere	in	manufactured gas	6.87E+09	MJ
EU	Heat	Total	Technosphere	in	nuclear fuel element	0.00E+00	kg
EU	Heat	Total	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Heat	Total	Technosphere	in	power capacity	4.46E+03	MW
EU	Heat	Total	Technosphere	in	solid fossil fuels	1.38E+09	kg
EU	Heat	Total	Technosphere	in	total oil products	5.61E+08	MJ
EU	Heat	Total	Technosphere	in	waste	0.00E+00	kg
EU	Heat	Total	Technosphere	in	water_techno	9.04E+09	l
EU	Heat	Total	Biosphere	in	land use	1.07E+03	ha
EU	Heat	Total	Biosphere	in	water_bio	6.82E+11	l
EU	Heat	Total	Biosphere	out	biomass	0.00E+00	kg
EU	Heat	Total	Biosphere	out	coal	0.00E+00	kg
EU	Heat	Total	Biosphere	out	gas	1.14E+11	m3
EU	Heat	Total	Biosphere	out	greenhouse gases	6.59E+10	kg CO2 eq.
EU	Heat	Total	Biosphere	out	lignite	0.00E+00	kg
EU	Heat	Total	Biosphere	out	oil	0.00E+00	kg
EU	Heat	Total	Biosphere	out	spent nuclear fuel	0.00E+00	kg

EU	Heat	Total	Biosphere	out	uranium	0.00E+00	kg
EU	Heat	Total	Biosphere	out	waste	1.50E+09	kg
EU	Heat	Total	Biosphere	out	water_bio	5.30E+11	l
EU	Energy Sector	Local	Technosphere	in	biofuels	1.97E+10	MJ
EU	Energy Sector	Local	Technosphere	in	biogas	8.23E+11	MJ
EU	Energy Sector	Local	Technosphere	in	coal products	1.63E+09	kg
EU	Energy Sector	Local	Technosphere	in	derived heat	8.16E+10	MJ
EU	Energy Sector	Local	Technosphere	in	electricity	1.25E+12	MJ
EU	Energy Sector	Local	Technosphere	in	human activity	4.00E+09	hrs
EU	Energy Sector	Local	Technosphere	in	manufactured gas	3.00E+12	MJ
EU	Energy Sector	Local	Technosphere	in	nuclear fuel element	2.01E+06	kg
EU	Energy Sector	Local	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Energy Sector	Local	Technosphere	in	power capacity	2.87E+11	MW
EU	Energy Sector	Local	Technosphere	in	solid fossil fuels	7.80E+09	kg
EU	Energy Sector	Local	Technosphere	in	total oil products	1.69E+12	MJ
EU	Energy Sector	Local	Technosphere	in	waste	7.60E+10	kg
EU	Energy Sector	Local	Technosphere	in	water_techno	4.58E+12	l
EU	Energy Sector	Local	Biosphere	in	land use	2.32E+05	ha
EU	Energy Sector	Local	Biosphere	in	water_bio	3.19E+15	l
EU	Energy Sector	Local	Biosphere	out	biomass	0.00E+00	kg
EU	Energy Sector	Local	Biosphere	out	coal	1.48E+08	kg
EU	Energy Sector	Local	Biosphere	out	gas	1.51E+11	m3
EU	Energy Sector	Local	Biosphere	out	greenhouse gases	1.73E+12	kg CO2 eq.
EU	Energy Sector	Local	Biosphere	out	lignite	0.00E+00	kg
EU	Energy Sector	Local	Biosphere	out	oil	6.88E+10	kg
EU	Energy Sector	Local	Biosphere	out	spent nuclear fuel	2.65E+06	kg
EU	Energy Sector	Local	Biosphere	out	uranium	0.00E+00	kg
EU	Energy Sector	Local	Biosphere	out	waste	1.23E+09	kg
EU	Energy Sector	Local	Biosphere	out	water_bio	3.18E+15	l
EU	Energy Sector	Externalised	Technosphere	in	biofuels	0.00E+00	MJ
EU	Energy Sector	Externalised	Technosphere	in	biogas	2.61E+07	MJ
EU	Energy Sector	Externalised	Technosphere	in	coal products	0.00E+00	kg
EU	Energy Sector	Externalised	Technosphere	in	derived heat	8.19E+09	MJ
EU	Energy Sector	Externalised	Technosphere	in	electricity	6.57E+10	MJ
EU	Energy Sector	Externalised	Technosphere	in	human activity	7.62E+09	hrs
EU	Energy Sector	Externalised	Technosphere	in	manufactured gas	7.50E+11	MJ
EU	Energy Sector	Externalised	Technosphere	in	nuclear fuel element	0.00E+00	kg
EU	Energy Sector	Externalised	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Energy Sector	Externalised	Technosphere	in	power capacity	0.00E+00	MW
EU	Energy Sector	Externalised	Technosphere	in	solid fossil fuels	0.00E+00	kg
EU	Energy Sector	Externalised	Technosphere	in	total oil products	5.02E+11	MJ
EU	Energy Sector	Externalised	Technosphere	in	waste	0.00E+00	kg

EU	Energy Sector	Externalised	Technosphere	in	water_techno	1.11E+12	l
EU	Energy Sector	Externalised	Biosphere	in	land use	2.30E+06	ha
EU	Energy Sector	Externalised	Biosphere	in	water_bio	6.68E+11	l
EU	Energy Sector	Externalised	Biosphere	out	biomass	0.00E+00	kg
EU	Energy Sector	Externalised	Biosphere	out	coal	3.51E+11	kg
EU	Energy Sector	Externalised	Biosphere	out	gas	6.54E+11	m3
EU	Energy Sector	Externalised	Biosphere	out	greenhouse gases	4.51E+11	kg CO2 eq.
EU	Energy Sector	Externalised	Biosphere	out	lignite	0.00E+00	kg
EU	Energy Sector	Externalised	Biosphere	out	oil	9.15E+11	kg
EU	Energy Sector	Externalised	Biosphere	out	spent nuclear fuel	0.00E+00	kg
EU	Energy Sector	Externalised	Biosphere	out	uranium	3.89E+06	kg
EU	Energy Sector	Externalised	Biosphere	out	waste	5.76E+09	kg
EU	Energy Sector	Externalised	Biosphere	out	water_bio	1.61E+11	l
EU	Energy Sector	Total	Technosphere	in	biofuels	1.97E+10	MJ
EU	Energy Sector	Total	Technosphere	in	biogas	8.23E+11	MJ
EU	Energy Sector	Total	Technosphere	in	coal products	1.63E+09	kg
EU	Energy Sector	Total	Technosphere	in	derived heat	8.97E+10	MJ
EU	Energy Sector	Total	Technosphere	in	electricity	1.32E+12	MJ
EU	Energy Sector	Total	Technosphere	in	human activity	1.16E+10	hrs
EU	Energy Sector	Total	Technosphere	in	manufactured gas	3.75E+12	MJ
EU	Energy Sector	Total	Technosphere	in	nuclear fuel element	2.01E+06	kg
EU	Energy Sector	Total	Technosphere	in	other hydrocarbons	0.00E+00	kg
EU	Energy Sector	Total	Technosphere	in	power capacity	2.87E+11	MW
EU	Energy Sector	Total	Technosphere	in	solid fossil fuels	7.80E+09	kg
EU	Energy Sector	Total	Technosphere	in	total oil products	2.20E+12	MJ
EU	Energy Sector	Total	Technosphere	in	waste	7.60E+10	kg
EU	Energy Sector	Total	Technosphere	in	water_techno	5.69E+12	l
EU	Energy Sector	Total	Biosphere	in	land use	2.53E+06	ha
EU	Energy Sector	Total	Biosphere	in	water_bio	3.19E+15	l
EU	Energy Sector	Total	Biosphere	out	biomass	0.00E+00	kg
EU	Energy Sector	Total	Biosphere	out	coal	3.51E+11	kg
EU	Energy Sector	Total	Biosphere	out	gas	8.05E+11	m3
EU	Energy Sector	Total	Biosphere	out	greenhouse gases	2.18E+12	kg CO2 eq.
EU	Energy Sector	Total	Biosphere	out	lignite	0.00E+00	kg
EU	Energy Sector	Total	Biosphere	out	oil	9.83E+11	kg
EU	Energy Sector	Total	Biosphere	out	spent nuclear fuel	2.65E+06	kg
EU	Energy Sector	Total	Biosphere	out	uranium	3.89E+06	kg
EU	Energy Sector	Total	Biosphere	out	waste	6.99E+09	kg
EU	Energy Sector	Total	Biosphere	out	water_bio	3.18E+15	l

A4. Curriculum Vitae

EDUCATION

Ph.D. Candidate, Institute of Environmental Science and Technology (ICTA), Autonomous University of Barcelona
October 2016 - present
PhD thesis title: "Energy systems are complex: implications for science and for policy". Funded by the Horizon-2020 MAGIC project (Moving Towards Adaptive Governance in Complexity: Informing Nexus Security)
Supervisors: Mario Giampietro and Maddalena Ripa

MSc in Global Change, Autonomous University of Barcelona
September 2015 to June 2016
MSc thesis title: "The feasibility, viability and desirability of a 100% renewable electricity transition in Spain"
Supervisors: Zora Kovacic and Mario Giampietro

First Class Honours BSc in Physics with a Year Abroad, King's College London
September 2010 to June 2014
BSc thesis title: "The modern demon: Entropy and the arrow of time"
Supervisor: Samjid Mannan

Student-At-Large, University of Chicago
September 2012 to June 2013
Physics, Art History & Visual Arts

Prizes & awards

King's myScholarship, 2012. Awarded to students who excelled in their studies and made an exceptional contribution to the life of the Department
Sambrooke Exhibition, 2011. Awarded to the first or second year student who obtains the best results
Dillon Prize, 2011. Awarded to the first year Physics student with the best final year performance

WORKSHOPS & SHORT COURSES

Complex Networks Winter Workshop (https://vermontcomplexsystems.org/events/cnww/), Québec City (QC - CA), December 2019
Energy & Environmental Justice Workshop, Institute of Environmental Science & Technology (Autonomous University of Barcelona), October 2019
Winter Workshop on Complex Systems (wwcs2019.org), Zakopane (PL), December 2018
Complex Systems Summer School, Santa Fe Institute (NM - US), June 2018

RECENT WORK EXPERIENCE

Project Co-ordinator, Complexity Interactive (virtual course), Santa Fe Institute (NM - US), October 2020
Project Co-ordinator, Complex Systems Summer School (CSSS), Santa Fe Institute (NM - US), June 2019
Community Liaison Officer, Progressio ICS at Gracias (Honduras), April 2015 to June 2015
Digital Media Assistant, Queen Elizabeth Prize for Engineering (QEPrize) at the Royal Academy of Engineering (UK), December 2014 to April 2015
Intern, Queen Elizabeth Prize for Engineering (QEPrize) at the Royal Academy of Engineering (UK), September 2014 to December 2014

Publications

Published journal articles
Ripa, M., **Di Felice, L.J.** & Giampietro. M. The energy metabolism of post-industrial economies. A framework to account for externalisation across scales.
Diaconescu, A., **Di Felice, L. J.**, & Mellodge, P. Exogenous coordination in multi-scale systems: How information flows and timing affect system properties
Kovacic, Z., **& Di Felice, L. J**. (2019). Complexity, uncertainty and ambiguity: Implications for European Union energy governance. *Energy Research & Social Science*, *53*, 159-169.
Di Felice, L. J., Ripa, M., & Giampietro, M. (2019). An alternative to market-oriented energy models: Nexus patterns across hierarchical levels. *Energy policy*, *126*, 431-443.
Parra, R., **Di Felice, L. J.**, Giampietro, M., & Ramos-Martin, J. (2018). The metabolism of oil extraction: A bottom-up approach applied to the case of Ecuador. *Energy policy*, *122*, 63-74.

Conference proceedings
Diaconescu, A., **Di Felice, L. J.**, & Mellodge, P. (2019, June). Multi-Scale Feedbacks for Large-Scale Coordination in Self-Systems. In *2019 IEEE 13th International Conference on Self-Adaptive and Self-Organizing Systems (SASO)* (pp. 137-142). IEEE.
Di Felice, L. J., Ripa, M., & Giampietro, M. (2017, September) Electric vehicles in the EU: between narrative and quantification. In *2017 10th Biennial International Workshop Advances in Energy Studies (BIWAES)* (pp. 390-399).

Submitted / Under review
Swain, A.*, Williams, S. **Di Felice, L. J**.* & Hobson, E. Interactions, information and emergence: Exploring task allocation in ant colonies using network analysis *(*contributed equally)*
Di Felice, L. J., Renner, A. & Giampietro, M. Are electric vehicles the answer? How narratives shape the framing of complex sustainability problems
Bontempi, A., Del Bene, D. & **Di Felice, L.J.** *Salini Impregilo* damming the South: Sixty years developing 'the poor'

Project deliverables & dissemination

MAGIC deliverables:

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

Di Felice, L.J., Ripa, M., Renner, A., Velasco-Fernández, R., Pereira, Â.G. & Giampietro, M. (2020), 'Decarbonisation of transport through innovation: the case of electric vehicles', MAGIC (H2020-GA 689669), Project Deliverable 6.9, 21 February 2020.

Di Felice L, Dunlop T, Giampietro M, Kovacic Z, Renner A, Ripa M and Velasco-Fernández R. Report on the Quality Check of the Robustness of the Narrative behind Energy Directives. MAGIC (H2020–GA 689669) Project Deliverable 5.4, 30 November 2018.

Krol MS, Cabello Villarejo V, Cadillo-Benalcazar J, de Olde E, Di Felice L, Giampietro M, Muscat A, Renner A, Ripa M, Ripoll Bosch R, Serrano-Tovar T and Verburg CCA. Report on exploratory applications of the MuSIASEM Toolbox in Quantitative Story Telling for anticipation. MAGIC (H2020–GA 689669), Project Deliverable 4.3, 31 March 2018.

Articles written for The Nexus Times

- Story-telling gorillas and sustainability discourses of the European primary sector (Ansel Renner & Louisa Jane Di Felice)
- Modelling energy systems as multi-scale systems (Louisa Jane Di Felice)
- Electric cars: An answer to the wrong question? (Louisa Jane Di Felice)
- What if energy imports mattered? (Maddalena Ripa & Louisa Jane Di Felice)
- Planetary boundaries and global food systems: What about the farmers? (Louisa Jane Di Felice, Mario Giampietro and Tarik Serrano-Tovar)
- Is renewable energy efficient? (Louisa Jane Di Felice)
- The paradox of efficiency: Can uncertainty be governed? (Zora Kovacic, Louisa Jane Di Felice & Tessa Dunlop)

CONFERENCE PRESENTATIONS

Energy systems are complex: Implications for science and for policy. Part of the shared panel “Governance in complexity”, at the International Seminar on Environment and Society, Lisbon, PT. March 2020
What is the purpose of electric vehicles? Reframing sustainable transport narratives in the EU. Presented at the 2nd International Conference on Energy Research and Social Science (ERSS), Tempe, USA. May 2019
The externalisation of the EU’s energy sector: policy implications of the nexus in a globalised world. Presented with Maddalena Ripa at the 1st ICTA-UAB Spring Symposium (ICTASS), Barcelona, ES. May 2018
Electric vehicles in the EU: between narrative and quantification. Presented at the 10th Biennial International Workshop Advances in Energy Studies (BIWAES), Naples, IT. July 2017

INVITED TALKS

Electric cars and efficiency: challenges of the energy transition. Presented (in Spanish) with Raul Velasco-Fernandez at *La Fàbrica del Sol,* as part of the EU Sustainable Energy Week. Barcelona, May 2020.

Energy and ecofeminism from an academic perspective. Presented (in Spanish) at the *Ecoserveis XXI Forum on Sustainable Energy: Energy and Gender*. Barcelona, March 2019

Rethinking energy: conversations from degrowth and environmental justice. Presented (in Spanish) with Fulvia Ferri and Sofía Avila at *La Fàbrica del Sol*. Barcelona, May 2018

Degrowth and energy: problems and alternatives in a consumption-addicted society. Presented (in Spanish) with Fulvia Ferri at *Nits Tematiques a La Floresteca*. Barcelona, February 2018

Renewable energy transitions beyond technology. Presented (in Italian) via video at the *Festival di Cultura Ecologica*. Rome, July 2017

TEACHING & SUPERVISION

Santa Fe Institute Complexity Interactive (SFI-CI), 2020. Co-ordination and facilitation of student projects (60+ students)

Santa Fe Institute Complex Systems Summer School (CSSS), 2019. Co-ordination and facilitation of student projects (80+ students)

Master thesis supervisor, 2019. Kathalina Peleger: "Narrative analysis of European and Latin American media. The controversial debate surrounding electric vehicles and lithium mining". Co-supervised with Maddalena Ripa

Borgofuturo Social Camp, **2016.** Workshop on energy transitions (held with Ansel Renner)

LIPHE4 Summer School, 2016/17/19. Classes on social metabolism and supervision of student-led projects

OTHER Ph.D. ACTIVITIES

- Editor of "The Nexus Times", with Zora Kovacic, Tessa Dunlop, Luis Zamarioli and Roger Strand (booklet with all articles here: http://ecgc.eu/megaloceros/book/the-nexus-times)
- Manager of the @MAGIC_NEXUS twitter account
- Manager of the Coursera online course "Sustainability of social-ecological systems: the nexus between water, energy and food"