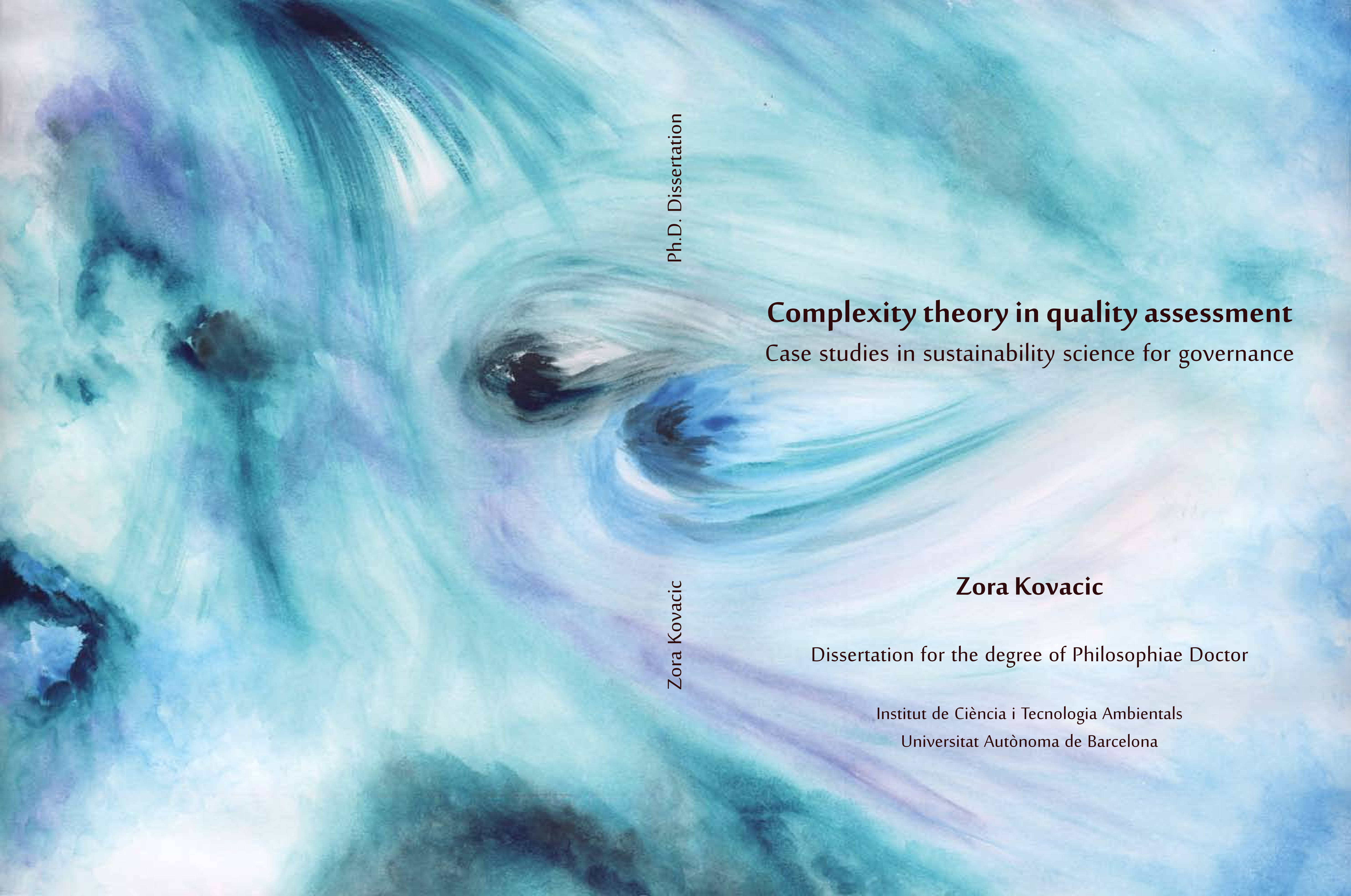

Ph.D. Dissertation

Zora Kovacic

Complexity theory in quality assessment

Case studies in sustainability science for governance

Zora Kovacic

Dissertation for the degree of Philosophiae Doctor

Institut de Ciència i Tecnologia Ambientals
Universitat Autònoma de Barcelona

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Abstract

This dissertation is an investigation of science-policy issues in the field of sustainability science that are characterised by high levels of uncertainty and complexity. I focus on situations in which the view of scientific knowledge as the best available knowledge is questioned and a plurality of non-equivalent knowledge claims exists within science. The purpose of this dissertation is to contribute to a better understanding of the challenges of complexity and uncertainty for the science-policy interface.

I argue that in the case of sustainability issues that are not well governed, the challenge is not just a matter of sloppy science or of corruption in either the scientific or political processes, but there is a need for (i) a better understanding of the implications of complexity and uncertainty for science for governance, and (ii) for a quality assessment of the representations of sustainability issues used to inform policy. In order to address this challenge, I apply the conceptual and analytical tools of complexity theory to quality assessment. I focus on the criteria of pertinence and usefulness as a way of carrying out both an epistemic and a pragmatic quality assessment.

More specifically, I provide a multi-scale representation of the issues considered and allocate the plurality of representations used for the governance of those issues to different scales of analysis. The approach developed does not offer any answers as to what is to be considered pertinent of useful, but it provides a representation of complexity that makes it possible to adopt a reflexive stance with respect to the pre-analytical choices and normative stands implied by different representations.

I apply these tools to three case studies in order to analyse how pertinence and usefulness unfold in practice. In the first case study, I analyse the pertinence and the usefulness of the mono-scale representations of the neo-classical economics knowledge base in the context of the financial crisis of 2007-08. In the second case study, I analyse the pertinence and usefulness of the plurality of representations and knowledge claims used in the governance of water in Israel. In the third case study, I analyse the pertinence and usefulness of the future visions of smart grids in the context of the European Union in relation to the complex energy systems of modern economies.

Resumen

Esta tesis es una investigación sobre los retos en el uso de las ciencias de la sostenibilidad en la interfaz entre ciencia y política caracterizados por un alto nivel de incertidumbre y complejidad. En concreto, se analizan situaciones en las cuales se cuestiona el ideal de la ciencia como mejor conocimiento disponible y donde además se encuentran una pluralidad de arquetipos de conocimiento dentro de la propia ciencia. El objetivo de esta tesis es el de aportar un entendimiento más amplio de los retos de la complejidad e incertidumbre para la interfaz entre ciencia y política.

Se argumenta que en el caso de problemas de sostenibilidad que no están bien gobernados, el desafío no es solo cuestión de ciencia mal hecha o de corrupción en los procesos científicos o políticos, sino que se necesita de (i) un entendimiento más amplio de las consecuencias de la complejidad e incertidumbre en la ciencia usada en los procesos de gobernanza, y (ii) una valoración de la calidad de las representaciones de los problemas de sostenibilidad usados para informar a la política. Para encarar este reto, se usan herramientas conceptuales y analíticas de la teoría de la complejidad para la evaluación de calidad. En concreto, el análisis se centra en los criterios de pertinencia y utilidad con el objetivo de efectuar una evaluación cualitativa epistemológica y pragmática a la vez.

Se proporciona una representación multi-escala de los problemas analizados y se ubican las diferentes representaciones usadas en la gobernanza de esos problemas en la escala de análisis correspondiente. La aproximación así desarrollada no proporciona respuestas en relación a qué tipo de información se debe considerar pertinente o útil, sino una representación de la complejidad que permite adoptar una actitud reflexiva con respeto a la decisiones pre-analíticas y posiciones normativas que forman parte de diferentes representaciones.

Estas herramientas se aplican a tres casos de estudio para analizar cómo los conceptos de pertinencia y utilidad se configuran en la práctica. En el primer caso de estudio, se analiza la pertinencia y la utilidad de las representaciones mono-escalares de la economía neo-clásica en el contexto de la crisis financiera de 2007-08. En el segundo, se analizan la pertinencia y utilidad de la pluralidad de representaciones y arquetipos de conocimiento usados en la gestión del agua en Israel. En el tercero, se analiza la pertinencia y la utilidad de las visiones futuras de las *smart grids* en el contexto de la Unión Europea en relación a la complejidad de los sistemas energéticos de sociedades modernas.

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Chapter 1

Introduction

1. Motivation

On September 2nd, 2009, Paul Krugman wrote on the New York Times:

> It's hard to believe now, but not long ago economists were congratulating themselves over the success of their field. […] The "central problem of depression-prevention has been solved," declared Robert Lucas of the University of Chicago in his 2003 presidential address to the American Economic Association. In 2004, Ben Bernanke, a former Princeton professor who is now the chairman of the Federal Reserve Board, celebrated the Great Moderation in economic performance over the previous two decades, which he attributed in part to improved economic policy making.

The financial crisis of 2008 makes one smile at these statements. There are many possible explanations of why some of the most prominent experts in economics were blind to the fragility of the economic system prior to the crisis. Some point at the limitations of economics as a discipline, at the inappropriate use of statistics, at the impossibility of predicting the future based on the observation of past trends, and so on. This type of argument can be seen as a criticism to the way scientific information is made, which can be referred to as sloppy science, shoddy science, or pseudoscience. A second line of arguments hold that the problem lays in the fact that scientific research is guided by political agendas, that research funding comes with vested interests, pointing at a problem of corruption. Symbolic of this argument is Sinclair's (1935) quote "It is difficult to get a man to understand something when his salary depends upon his not understanding it."

I argue that Krugman's example also reveals a third fundamental problem in the science-policy interface, which can be found in economics as well as in other fields, and which is the focus of my dissertation. As I will try to show throughout this dissertation, the problem cannot be reduced only to a matter of sloppy science – it can hardly be argued that the Nobel laureate Lucas is not a competent scientist – nor to a matter of corruption. The problem is dealing with complexity and uncertainty, both in the definition of the issues and in the scientific and political processes governing them.

In order to explore this problem, I will start by introducing and defining my object of study, the science-policy interface in section 1.1. In relation to the scientific knowledge base, in section 1.2 I proceed to analyse the role of simplification in dealing with complex sustainability issues. In section 1.3 I return to the criticisms of quantitative science by giving more specific examples of the problems associated with simplification. In section 1.4, I discuss more at length the concept of uncertainty and its relation to the problems associated with quantitative representations of sustainability issues. The concept of complexity, being central to this dissertation, will be explored at length in section 5. In section 1.5 I give a brief outline of the contributions of this dissertation.

1.1 The interface between science and policy

Increasingly in sustainability science, it is recognised that there are serious problems in the use of quantitative information for governance. A flourishing literature denounces a variety of issues associated with excessive faith in numbers (Porter 1995; Saltelli and Funtowicz 2013), with failures in making predictions about the future (Pilkey and Pilkey-Jarvis 2007; Savage 2009; Taleb 2007), with the limited usefulness of idealized mathematical models in dealing with complexity and uncertainty (Chu 2013; Fine and Milonakis 2009; Spangenberg and Settele 2010), and with the misuse and misinterpretation of quantitative information in policy-making (Funtowicz and Ravetz 1990; Reinert 2009), to give but a few examples.

The problems flagged by these authors are not simply a matter of sloppy science, but rather flag science-policy issues that are not well governed, the limitations of quantitative scientific information about sustainability that is used in governance, and a poor appreciation of uncertainty and complexity. I analyse science-policy issues in situations in which the view of scientific knowledge as the best available knowledge is questioned and in which there is a plurality of competing knowledge claims within science.

The purpose of this dissertation is to contribute to the understanding of the science-policy interface for such issues. A better understanding of the challenges of complexity and uncertainty for the science-policy interface is helpful in the study of contradictions, controversies, communication breakdowns and knowledge insufficiencies in the governance of sustainability issues.

I address this need by investigating the methodology and epistemology of sustainability science and its use in policy. I analyse the scientific information about sustainability issues that is used for governance, whether in guiding decision-making, in reinforcing or in disputing the existing political processes, policies and institutions. The focus is on the meeting point between (a) the scientific processes that produce quantitative representations of sustainability issues, and (b) the political processes that use these representations.

Questions of complexity and uncertainty call for a quality assessment of the knowledge base used in the governance of sustainability issues. For this reason, the science-policy issues analysed are a matter of scientific research, and not only of scientific practice or politics. A theoretical understanding of the challenges posed by uncertainty and complexity to the science-policy interface is necessary to address the sustainability issues analysed.

1.2 The role of simplification

This dissertation addresses the need for a better understanding of the challenges that complex sustainability issues pose to the knowledge base used for governance. In referring to science for governance, I do not imply that all governance processes are based on, or make use of, scientific information, nor do I refer to all science, but rather I focus on the specific type of scientific information that is produced to be used in governance. This section gives an overview of how knowledge is mobilised at the science-policy interface with the aim of simplifying complexity.

The sustainability issues considered in this dissertation are characterized by a plurality of competing knowledge claims and contradictory representations, which makes it difficult to formulate policy recommendations. Rittel and Webber (1973), in their discussion of public contestations of professional knowledge, coined the term "wicked problem" to refer to problems for which there is no exhaustive formulation containing all the information needed to understand and deal with the problem. Giampietro el at. (2006) define sustainability problems as complex issues, which can be simultaneously described from multiple scales of analysis and multiple dimensions (for a more thorough discussion of complexity, see section 5). The problem resides in the fact that one single observer cannot consider simultaneously all the possible perceptions and representations of the object under study across scales and dimensions (Giampietro et al. 2011).

Simplification is necessary in order to produce scientific information that can be used for governance. Producing a representation that is as elaborated as the issue that is described is not useful for action. An example of the tension between the completeness of the information and the usefulness of the representation is given by Jorge Luis Borges. As the tale *On Exactitude of Science* (1658) narrates, the cartographers of an ancient empire made a map of the size of the empire in order to represent its entirety. However, the map was considered useless by the following generations and destroyed. A map of the size of the empire does not give any additional information, time saving or guidance, than travelling the whole empire.

Simplification thus makes it possible to produce what Guimarães Pereira and Funtowicz call "policy-relevant science" (2009).

Georgescu-Roegen (1971) identifies a similar tension between the contemplation of the whole and the abstraction required by logical reasoning. In relation to this issue, Georgescu-Roegen characterises science as the activity of making "heroic simplifications and totally ignor[ing] their ultimate consequences" (1971: 212). Many and very different definitions of science are available in the literature and I will return to some of them in section 2. However, a comprehensive discussion of how science has been defined through history and by different scholars is out of the scope of this dissertation. What I wish to highlight here is the need for simplification in the production of scientific information.

Simplification can be defined in a variety of different ways, as a way of *managing* the external world (Zellmer et al. 2006), of focusing on the *essence* of the system under study (Chu 2013), or of defining the *relevant* characteristics of the system (Giampietro 2003). These different definitions point at different types of information produced through simplification that have different uses in guiding action. As Rittel and Webber point out, the information used to represent a problem "depends on one's idea for solving it" (1973: 161).

As a consequence, the usefulness of the representation can be in dispute. When the usefulness of scientific information is questioned, the modern model of the use of science for governance (Funtowicz and Strand 2007) is also questioned. Funtowicz and Strand define the modern model as based on the assumption that scientific information can tell "the policy maker everything that is necessary to know in order to decide for the common good" (2007: 264). In the presence of irreducible uncertainty and complexity, scientific information cannot be complete. In the sustainability problems I analyse, simplification implies a distancing from the completeness of the representation. As a consequence, the use and the usefulness of the representation cannot be taken as given. The next section introduces some of the problems of simplification and their consequences for the science-policy interface.

1.3 Problems of simplification

However necessary simplification may be, when using the representations produced through simplifying assumptions for governance, it is important to be aware of the limits of these representations. As Box succinctly put it, “essentially all models are wrong but some are useful” (1987). Simplification is problematic when it produces useless information. This section gives an overview of some of the problems of simplification, namely questioning the usefulness of simplifications in informing policy, the informative power of commonly used indicators, the necessity of quantitative measurements in certain situations, the objectivity of numbers, and the usefulness of mathematically valid models based on oversimplifying assumptions.

The first problem refers to the consequences of simplification in policy-making. Reinert (2009) talks of “terrible simplifiers” to refer to simplifications that are not useful for guiding policy. Reinert uses the Millennium Development Goals as an example of terrible simplifiers, criticising such goals for curing only the symptoms and not the causes of poverty. The Millennium Development Goals set goals in general terms for the whole world, overlooking the differences in the structure of the economy of individual countries, the qualitative differences between the activities of the countryside and those of the cities, and the differences between individual economic agents (Reinert 2007). Reinert argues that such differences are the cause of inequality and underdevelopment, and that a policy based on averages is ineffective in tackling these causes. The problem of terrible simplifiers thus consists in the application of models based on simplifying assumptions to complex issues.

Another example is the case of payments for ecosystem services. Spangenberg and Settele (2010) argue that monetary valuations of ecosystem services are a good example of how the use of economic models based on methodological individualism fails to provide any information useful for guiding environmental policy, because it neglects other scales of analysis and other definitions of value developed in ecosystem science. Creating new markets in order to account for ecosystem services does not lead to a better management of these services but to a perpetuation of the current management.

The second problem identified is that simplifications limit the capacity to convey information. A renowned example is the Gross Domestic Product (GDP). Although the use of a standardised measure makes it possible to compare the performance of different countries, GDP has been heavily criticised for not distinguishing among positive and negative impacts on wellbeing, as war and natural disasters may result in an increase in GDP, for not taking into account environmental impacts, inequality and gender issues, work conditions, health and intangible capital (EC 2009), and for not taking into account consumption possibilities, changes in wealth, distribution issues and non-market activities including leisure (Stiglitz et al. 2009). In this case, simplification leads to a loss of relevant information to which the critics of GDP bring attention.

The third point addresses the question: are quantitative measurements always necessary? The use of quantitative measurements to represent complex sustainability issues, such as sustainability indicators, is another type of simplification. An eloquent example of the limited usefulness of quantitative representations abstracted from context is given by Munda (2013). Munda argues that the Index of Sustainable Economic Welfare is so aggregated that it does not provide any clear information on the cause of its bad performance, making it useless for policy-making (2013: 2). The insistence on quantitative measurements, especially in monetary terms, is seen as counterproductive when it comes to promoting alternative worldviews, ethical valuations and environmental concerns (Martinez-Alier et al. 1998; Funtowicz and Ravetz 1994). These criticisms indicate that quantitative measurements may not add any useful information to the problem framing.

The fifth problem regards the ideal of objectivity associated with quantitative measurements. As Porter (1995) points out, the ideal of objectivity associated with numbers has created the perception that quantitative science can be trusted. Funtowicz and Ravetz (1990) offer a number of examples of misuses of quantitative information. As illustrated by the fossil joke, mathematical accuracy is meaningless in the presence of high uncertainty. The joke refers to a museum attendant telling visitors that some fossils were 56,000,012 years old. When asked how he knew, he explained that when he started the job 12 years before, he was told that the fossils were 56,000,000 years old (Funtowicz and Ravetz 1994a).

As Funtowicz and Ravetz (1990) explain, in expressing the age of the fossil, the zeros have the function of fillers and not of counters. That is, the zeros indicate the order of magnitude at which the age of the fossil is estimated, not an exact measure. Funtowicz and Ravetz argue that craft skills are required in order to make this distinction. The confusion about the role of zeros illustrates how the use of numbers does not eliminate vagueness or ambiguity. Additional knowledge is required about the meaning and intended use of mathematical notation in different contexts.

Finally, there is a problem associated with the rhetorical use of quantitative information (Saltelli et al. 2013). This criticism points to cases in which models are used because they are mathematically sound, not because they are useful. Fine and Milonakis (2011) criticise economics for being “useless but true.” They argue that economic models are mathematically valid but lack any practical relevance because of the large number of assumptions on which those models are based, such as perfect knowledge, complete preferences, *ceteris paribus*, and so on. Pilkey and Pilkey-Jarvis (2007) also speak of useless arithmetic in relation to environmental science. In this case, the object of contention is the use of the representations of sustainability issues in guiding policy, not the technologies or the scientific knowledge itself.

The concept of usefulness is prominent in many of the criticisms posed to quantitative information. This critique can be related to the debate over what constitutes quality in scientific knowledge. Three definitions of quality are relevant to this debate, adapted from Funtowicz and Ravetz (1992):

(a) The substantive definition, where quality refers to the truthfulness of the scientific information. The quality of scientific information resides in science's ability to describe the world as it is, as exemplified by the view of science speaking truth to power. Funtowicz and Ravetz (1992) refer to this definition of quality as the classical view;

(b) The epistemological definition, where quality is ensured by the rigour of the methods deployed. The truthfulness of the representation cannot be known, as is the case of climate predictions for the distant future, and quality refers to how scientific information is produced, that is, to the craft skills of the scientists. This definition can be associated to what Funtowicz and Ravetz (1992) call the modern view; and

(c) The pragmatic definition, where quality refers to the fitness for purpose of the scientific information produced in relation to a specific use. In the context of pluralism, quality is seen as necessarily subjective. Instead of defining quality in absolute terms, a more pragmatic approach is taken and scientific knowledge is evaluated according to its usefulness. The latter view can be related to Funtowicz and Ravetz's (1992) definition of post-modernity.

In the sustainability issues I analyse, the correct application of scientific methods does not necessarily ensure the fitness for purpose of the representations analysed. For this reason, I refer both to the epistemological and pragmatic definitions of quality. In the next section, I discuss in more detail the challenges of assessing quality in these terms.

1.4 Dealing with uncertainty

The difficulties involved in the assessment of the usefulness of quantitative information can be understood as difficulties in dealing with uncertainty, broadly defined as any deviation from deterministic knowledge (Walker et al. 2003). Uncertainty is a salient feature of complex sustainability problems that refer to unknown future states, dynamic open systems, a plurality of social actors, and so on. In this section, I refer to the various definitions of uncertainty found in the literature and their implication for the science-policy interface.

Wynne (1992) identifies four different levels of uncertainty, namely risk, strict uncertainty, ignorance and indeterminacy. The distinction between risk and uncertainty were first introduced by Knight (1921) in relation to the study of stock markets. Knight defines risk as a situation in which the possible outcomes are known and the probabilities related to such outcomes can be calculated. Funtowicz and Ravetz (1990) refer to this as technical uncertainty. The definition of risk provided is based on a well-structured definition of a technical problem. For this reason, Taleb (2007) argues that risk only applies to the realm of Casinos, where all possible outcomes are well known.

Strict uncertainty refers to a situation in which the outcomes are known but their associated probabilities cannot be calculated. Uncertainty in this sense refers to the methodological uncertainty (Funtowicz and Ravetz 1990) involved in modelling, or in the representation of the observed system. Maxim and van der Sluijs locate the uncertainty related to model structuring in the limitations encountered when describing and measuring complex systems (2011: 484). In this case, complexity is a source of uncertainty. According to this view, uncertainty can be seen as the result of forcing the observed system into the theoretical boxes provided by the formal method of representation used.

A higher degree of uncertainty can be identified at the epistemological level, namely ignorance. Wynne defines ignorance as a situation in which "we don't know what we don't know" (1992: 114). In the case of ignorance, the outcome space is unknown. One is faced with the limits of knowledge, that is, with the limited capacity of the analyst to understand the observed system. The underlying assumption entailed by this definition is that ignorance can be reduced by increasing knowledge. Uncertainty in the case of ignorance can be described as a problem of framing (Walker et al. 2003). According to Harremoes and Turner (2001), integrated assessment as a methodology is designed precisely to deal with framing uncertainty by recurring to multiple disciplines and their relative perspectives.

Finally, another step up can be taken in the uncertainty spectrum, leading to indeterminacy (Wynne 1992). Indeterminacy can be seen as ontological uncertainty, that is, a situation in which "the formulation of the problem … is in itself dynamic" (Cañellas-Boltà et al. 2005: 95). Uncertainty in the case of indeterminacy has to do with the problem identification (Walker et al. 2003) and with the openness of the observed system. That is, indeterminacy arises when the relation between the observer and the observed system changes in time and as a consequence the perceptions of causality relations change in time. Theoretical ecology and evolutionary biology operate in the realm of indeterminacy. The work of Ulanowicz on ecosystem dynamics (e.g. Ulanowicz et al. 2009), Holling's analysis of adaptive cycles (Holling and Gunderson 2002) and Rosen's (1985) study of anticipatory systems, are examples of possible approaches to indeterminacy issues.

It should be noted that in going from risk to indeterminacy, the sources of uncertainty are increasing, but not necessarily the relevance of the uncertainty for the quality of the scientific information. Risk can be as serious a problem in ensuring or assessing the quality of scientific information as indeterminacy. Funtowicz and Ravetz (1990) argue that risk is commonly measured as a function of likelihood of harm from an unwanted event. "Measuring likelihood … [is] an inevitably inexact operation. The events themselves may not yet have occurred, or may be extremely rare; relevant data may be very hard to come by" (Funtowicz and Ravetz 1990: 80). It follows that risk should not be underestimated as a source of uncertainty in the evaluation of quantitative information used for governance. Uncertainty is classified as a series of ascending levels because higher levels of uncertainty include the lower one(s).

Complex sustainability issues are characterised by varying degrees of uncertainty. Quantitative scientific information can be seen as a way to calculate risk, to cope with uncertainty, and to reduce ignorance (Hacking 1990). However, in a situation of indeterminacy, science can be seen as a source of uncertainty (Funtowicz and Ravetz 1990; Refsgaard et al. 2006; Beck et al. 1994). The example of smart electric grids, which I will return to in chapter 4, is a point in case. The use of automated electricity grids is, on one hand, a way to deal with the uncertainty associated with the challenge of integrating renewable energy sources in the energy system by collecting information related to electricity consumption and production patterns. On the other hand, the access to, and use of, the collected information raises important privacy concerns (Hildebrandt 2013; Kostyk and Herkert 2012). In this sense, additional uncertainty is added to the system related to the use of technology.

Maxim and van der Sluijs identify three dimensions that can be used to analyse uncertainty, namely "substantial (the content of the knowledge itself), contextual (the context of knowledge production and use …), and procedural (the processes of how knowledge is framed, produced, communicated, or used)" (2011: 488). While touching upon all three dimensions of uncertainty, this dissertation focuses on the *procedural uncertainty* involved in the problem framing and, more specifically, in the pre-analytical choices. The procedural dimension of uncertainty is analysed from an epistemological perspective, that is, by assessing how the chosen representations of sustainability issues can be related to different levels of uncertainty.

I assume in all case studies that the models are used correctly and the sums are right. I do not analyse the social, cultural, political, or historical context motivating the choice of models and indicators used in each case study. My focus is on the identification of the pre-analytical assumptions implied by different representations and on how these choices affect the description of the problem under study.

Nevertheless, the seriousness of the uncertainty associated with content and context should not be underestimated. An example highlighting the importance of substantive quality control on the scientific information used for governance is given by Mayumi and Giampietro (2010), who denounce the use of dimensional arguments in logarithmic functions in standard economic models, which imply the existence of squared dollars, cubed dollars, and so on. Logarithmic functions should only be applied to a-dimensional variables. Examples of such practice include the Arrow-Domar growth theory, the Cobb-Douglas production function and the Kuznets curve (Mayumi and Giampietro 2010; Mayumi et al. 2012).

The science-policy interface is characterised by a plurality of different approaches to uncertainty. Van der Sluijs and colleagues (2010) identify three scientific approaches to uncertainty, namely: (i) the deficit model, in which uncertainty is seen as a temporary knowledge gap that can be quantified through statistical estimates; (ii) the consensus model, in which experts come to an agreement over plausible models and assumptions as in the case of the Intergovernmental Panel on Climate Change; and (iii) the extended community model, in which openness about ignorance opens the debate to the consideration of different legitimate perspectives beyond science. Different political approaches to uncertainty can also be identified, including (i) overselling certainty as in the case of global warming, and (ii) overemphasising uncertainty as in the case of health risks from smoking (Oreskes and Conway 2010). At the meeting point between science and policy, the representations that are used become also the battlefield between these different approaches to uncertainty.

1.5 My contribution to the debate

Building on the previous discussion, the challenge of simplification can be now defined as how to produce useful scientific information when dealing with high levels of uncertainty. Simplification is a necessary part of the production of policy relevant scientific information. There is nothing wrong with simplification *per se*. The problem arises when simplification is imposed upon the world and idealised models are used to understand complex issues neglecting the epistemological implications of the compressions required to build them. Taleb (2007) refers to this problem as “Platonifying reality,” that is, forcing reality into the Platonic ideal. A similar argument is made by Krugman (02/09/2009), who asserts that economists confuse beauty with truth, that is, mathematically valid models are taken to be faithful representations of the economy because of their theoretical soundness. The criticisms reported above should thus not be reduced to a matter of “shoddy science” (The Economist 19/10/2013), nor of political interests interfering with the scientific process (Lakoff 2010), although these might be part of the problem. According to Lakoff (2010) simplification leads to “hypocognition,” that is, the use of a limited framing of the issue, which limits one’s understanding of complexity. Therefore, there is a need for the assessment of the quality of the quantitative representations of sustainability issues used for governance.

A variety of concepts and criteria are used in the Knowledge Quality Assessment of science for policy (see for example Guimarães Pereira and Funtowicz 2009), including usefulness, relevance, pertinence, legitimacy, transparency to name but a few. A variety of different definitions of the above mentioned criteria are used depending on the approach or framework of reference. In this dissertation I focus on the concepts of pertinence and usefulness in order to take into consideration both the descriptive and normative aspects of the scientific representations under analysis.

Pertinence is defined as the consistency between the representation and the problem framing, and consists of an epistemological quality assessment. Usefulness is defined as the consistency between the information given by the representation and the stated goals of the analysis, and corresponds to a pragmatic approach to quality assessment. These definitions are based on the literature on hierarchy theory, a branch of complexity theory, which I will return to in section 5.

I will look at three case studies concerning the use of scientific information in the financial crisis of 2007-08, in the management of water in Israel and in the evaluation of smart grids as an emerging technology in the EU context. These three case studies are examples of complex sustainability issues that offer very different perspectives on the science-policy interface. What the three case studies have in common is the preponderant use of quantitative information in order to deal with uncertainty and with the controversies that surround these issues.

The contribution of complexity theory is to provide a mapping of the different descriptions of the problems analysed and to highlight the co-existence of an "irreducible pluralism" (O'Connor 1999) of different representations. I will offer throughout the case studies a multi-scale representation of the issues considered, which allows me to analyse and link the different descriptions found in the literature to multiple scales of analysis and to offer an alternative explanation of the sources of controversy. The approach developed in this dissertation does not offer any answers as to what is to be considered relevant or useful, but it offers a map to navigate through contradicting points of view. Put in a different way, this approach makes it possible to adopt a reflexive stance with respect to the pre-analytical choices involved in quantitative representations.

The remainder of the introduction is structured as follows. In section 2, I set the theoretical context of this dissertation through a brief historical overview of the debates in philosophy of science surrounding the use of science for governance. More specifically, I focus on the implications of pluralism for governance. I then introduce the field of sustainability science and comment on how this field relates to the debates in philosophy of science. In section 3, I frame the issues of simplification and of the quality assessment of quantitative information used for governance in terms of pre-analytical choices. This section introduces the jargon of the selected scholars within sustainability science and complexity theory to whom I refer throughout my dissertation. Having defined the motivation for this study, the academic context and the problem framing, I define the research questions and objectives in section 4. In section 5, I explain how the concepts and approach of complexity theory are deployed to define the analytical tools used to answer the research question. I give an overview of similar approaches to the assessment of the science-policy interface and highlight the strengths and limitations of the methodology developed in this dissertation. Section 6 introduces the case studies, highlighting their relevance to the research topic and to the research question.

2. Context

The following section contextualises the investigation carried out in this dissertation in its wider research field. I will start by defining the schools of thought and the historical context through which the field of science studies has emerged. I explore how the issue of quality assessment of the science-policy interface is addressed in the context of philosophy of science and how the debate evolved over time. In section 2.2, I focus more specifically on the different models for the study of the science-policy interface in the context of complexity and pluralism. I introduce the concept of reflexivity, central to the assessment of scientific representations of sustainability issues carried out in this dissertation. Section 2.3 further defines the research field within which the science-policy interface is examined, namely sustainability science. I provide a brief overview of how sustainability science relates to the debates in philosophy of science and to pluralism.

2.1 The historical context

The approach I have introduced so far assumes epistemological pluralism, that is, the existence of a plurality of ways of knowing. In this section, I take a glance at some of the debates in philosophy of science to show how these fields themselves have moved from the assumption of the modern model of science as producing the best available knowledge to epistemological pluralism. I give an overview of this development by highlighting some of what is at stake in the selected debates in philosophy of science. This section does not provide a comprehensive account of philosophy of science, but rather a selection of the aspects relevant to this dissertation.

The pragmatic definition of quality as fitness for purpose drives the attention towards the purposes behind specific formulations of what science is and what science does. In order to understand the purpose behind specific representations of science, it is useful to look at the historical context of different debates. Along this line of thinking, Rommetveit et al. (2013) trace the view of “science speaking truth to power” back to the Scientific Revolution of the Seventeenth Century, with Descartes, Copernicus, Galilei, Leibniz and many others. Modern science was born at that time in reaction to the dogmatic knowledge offered by the Church and as an attempt to re-establish order in a Europe ridden by chaos, the Thirty Years War and witch hunting. In this context, the quest for Truth is a quest for objective ways of knowing, for rational thinking based on mathematical language that would make it possible to move beyond religious disputes (Ibid).

The debate about reason was further developed by Locke, Hume and Boyle. Those philosophers hold that the mind is originally a *tabula rasa*, which acquires knowledge through experience (Shapin and Schaffer 1985). However, Hume contends that one’s senses cannot be trusted. The theory of knowledge as based on sense perception is used to create scepticism towards sense experience and the ability of reason to overcome passion (Letwin 1965). One should rather rely on the scientific method. The scientific method is seen as the most appropriate method of knowledge production, in as far as it is based on virtues such as self-abnegation and ensures disinterestedness. According to Boyle, the experiment is the most appropriate means of acquiring knowledge because the use of instruments makes it possible to identify “matters of fact,” independent from the judgment, reason or identity of the scientist (Shapin and Schaffer 1985). This school of thought also has its historical roots in the Enlightenment, and the praise of the scientific method was one of the arguments used in favour of reforming society through reason and away from faith and chaos.

This overview of the origins of modern science draws attention to the fact that modern science was conceptualised from early on as the voice of reason meant to guide and inform policy. However, the study of the science-policy interface only became the subject of academic disciplines in the Twentieth Century. I will give a brief overview of the main schools of thought in the philosophy of science related to the issue of quality in science for governance.

In the 1920s and 1930s, the debate about the scientific method developed in a further dispute between the Logical Positivists of the Vienna Circle and Popper's critical rationalism. Logical positivism combines empiricism, logic and reason in order to argue that only empirically verifiable statements should be accepted. The historical context of logical positivism is, once again, very revealing, as this school of thought emerges in the context of the rise of Nazism. Neurath explains that "logical empiricism is fighting metaphysical idealism," such as the use of Plato's Republic "where the Nazis found fine arguments for persecution, for destruction of mentally or bodily weak people and for teaching children to be cruel" (1946: 503). The argument that science describes the world as it is, can thus be understood as a way of re-establishing order and rationality in a war-riddled Europe. Neurath (1946) reconciles the existence of a plurality of experiences with the infallibility of empiricism by arguing that apparent differences in perception by different disciplines should be seen as complementary views of the world, and calls for an "orchestration of sciences."

On the other side of the debate, Popper (1963) held that evidence can only be used to rule out theories, that is, empiricism can only falsify scientific claims, not prove them. The distinction between science and non-science (or uncritical scientism in Popper's terms) is set by human ignorance, which scientists try to overcome by relying on a religious-like "belief in the omnipotence of the methods of pure science" (Hayek 1941: 20). The question asked to check the quality of the scientific representations is: "When is a theory true?" (Popper 1963: 33). Both in the logical positivism school and in Popper's thought, the question of quality is approached as a problem of correct application of the scientific method, which is assumed to reveal the true facts of nature. In other words, scientific representations are seen as value-free.

A further critique of the scientific method can be found in the later work of Feyerabend. According to Feyerabend (1975), the bias of science is due to the boundaries imposed by the scientific method. Feyerabend goes on to argue that theoretical anarchism would encourage the progress of science. What these authors have in common is the belief in the possibility for *good* science and in the progress of science. The problem seems to lie in the practices associated with the scientific community, and the scientific method. The novelty of Feyerabend's argument is the questioning of the assumption that the scientific method is value-free.

The debate about the demarcation between good science and bad science became particularly relevant in the 1960s, in the aftermath of the nuclear bombs and gas chambers of World War II and under the threat of the Cold War. The view of science as value-free was challenged by a variety of schools of thought. Science and its products came under scrutiny, leading to the creation of what is now called Science and Technology Studies (STS). Kuhn is seen by STS scholars (Barnes 1982) as the first to study how scientific knowledge is validated by the scientific community. According to Kuhn, scientific knowledge develops from cycles of "routine carrying on of a given form of scientific life, employing accepted procedures along the lines indicated by accepted standards" (Barnes 1982: 11), which are overcome by scientific revolutions, that is, radical innovations that later become established practices themselves. The innovation introduced by STS to the study of science consisted in grounding the understanding of scientific processes in their historical context.

Developing this line of research, Sociology of Scientific Knowledge emerged in the 1970s as the study of how scientific knowledge is influenced and influences social practices and of how scientific practices are a product of their social context. The significant brake from previous schools of thought is that scientific representations of the world come to be seen as value-laden. The use of scientific information for governance is seen as a social practice that needs to be explained with reference to the specific historical and political contexts that make it possible.

The raising scepticism towards the use of modern science in the political process led to the foundation of the Strong Programme. According to Bloor (1976) and Barnes (1974), the production of scientific knowledge has to be understood in relation to its social, political, economic and historical context. Scientists understand the world according to the culture and values of the society they are part of. The Strong Programme had the aim of revealing the “utilitarian goals which have long informed our science” (Bloor 1981: 201). This attitude is also expressed by Lyotard, who speaks of postmodernism as “incredulity toward metanarratives” (1979: xxiv) and towards the legitimacy of science. Notably, the Strong Programme emerged in the context of the Vietnam War and the protests and social movements of 1968.

Social Constructivism takes a step further in the role given to the value-laden representations of the world produced by science. Latour and Woolgar (1979) argue that facts themselves are constructed by the social reality in which scientists operate, rather than derived from the observation of reality. Knorr-Cetina (1981) argues that scientific knowledge is a product of culture, it is locally situated and context-impregnated. She deconstructs the idea of science as universal knowledge, as argued by the Vienna circle, and stresses that knowledge is always embedded in a specific epistemic culture. According to this school of thought, knowledge can be considered as an ontological entity influencing the way one perceives so-called matters of fact.

Both the Strong Programme and social constructivism bring the analyst to the forefront by highlighting the subjective character of scientific knowledge. In this sense, the possibility of defining the world objectively, or independently from the social context of the analyst, is forgone. The concept of value-laden representations of the world refers to the acknowledgement that beliefs and social norms influence one’s perception of the world. The use of scientific information for governance is then a social choice, a political choice, a cultural choice.

The epistemological turn of STS caused some discomfort within the scientific world, as epitomised by the Science Wars of the 1980s and 1990s (Hacking 1999). The implication of recognising the value-laden nature of scientific knowledge, poses important limits to the view of science as neutral, and therefore to its authority and legitimacy. Holton interprets this debate as a “battle between practitioners of science” and ideologically motivated groups who try to discredit science (1993: x). Critiques to the claim of infallibility and universality of science are perceived as a "rejection of the rationalist tradition of the Enlightenment" (Sokal and Bricmont 1999). Postmodernism comes to be seen as sterile relativism, anti-science (Holton 1993), and fashionable nonsense (Sokal and Bricmont 1999). The controversy turned into mutual accusations of hidden motives and political agendas.

This debate led to a split between those trying to restore rationality and to establish the correct way of interpreting science and those offering a way to cope with epistemological pluralism. The central question focused on the appropriate use of scientific information for governance, which was resolved in two ways. One approach is to define what a good use of scientific information is. On the other side, the recognition that there is a plurality of perspectives in society makes it problematic to define what is good in absolute terms.

An example of restoring the good use of scientific information is offered by the Public Understanding of Science approach, which holds that educating the public in science will dissipate doubts about the validity of scientific knowledge. This view is based on the simplifying assumption that people are rational and would therefore accept what is viewed as objective and neutral knowledge (Wynne 1975). Rationality in this context is defined according to a deterministic understanding of human behaviour, whereby individual actions and choices can be predicted based on their knowledge (Simon 1955). Hence, scientific knowledge will lead to consensus among scientists and the public.

Rationality is defined through axiomatic definitions of reason, such as self-interested utility maximisation, which resonate with the Cartesian praise of reason (O'Connor 1999). This way, the existence of a plurality of perceptions is reduced to the notion of human beings as primarily self-interested and reconciled with reason at the abstract level of statistical aggregates. This definition of rationality has been largely contested by Simon's work on bounded rationality (e.g. 1955), further developed by Tversky and Kahneman (e.g. 1981) and their studies on cognitive and heuristic processes used to make decisions under uncertainty.

Harding's Strong Objectivity (1993) and Martinez-Alier's Environmentalism of the Poor (2003), while taking the opposite stand and accepting that any representation of the world is necessarily subjective, are also based on a scientific rationale establishing *a priori* whose views are legitimate, and what those views consist of. Standpoint epistemology does not argue for an objective way of knowing but engages with the idea of value-laden knowledge to defend a certain set of values (for example, feminism or environmentalism). Standpoint epistemology "argues persuasively that the sciences have been blind to their own sexist and androcentric research practices and results" (Harding 1993: 53). In this case, revealing such blindness is seen as a way to restore the appropriate use of scientific knowledge. However, in contrast with the Public Understanding of Science approach, the appropriate use of science is defined in explicitly political terms.

The recognition of epistemological pluralism, on the other hand, led to the development of social epistemology, that is, the study of the divisions in the knowledge base within society. Fuller (1988) insists on the irreducibly social character of scientific knowledge by studying the social phenomena that reproduce the practices and perception of science. Social epistemology raises the questions: What type of knowledge do "we" want? How is that "we" defined? (Fuller 1988).
A similar approach was put forward by Jasanoff (2005) with her concept of civic epistemologies, based on the theory of co-production of knowledge. According to Jasanoff, the products of science "embody beliefs not only about how the world is, but also how it ought to be" (2004: 19) so that the use of certain scientific representations is linked to the establishment of institutions, identities and discourses. This view is in stark opposition to standpoint epistemology. As Jasanoff puts it, "how … can a sceptical and reflexive stance in relation to scientific knowledge be reconciled with making authoritative recommendations for social policy?" (1996: 393).
The 1990s further see the emergence of Mode 2 science (Gibbons et al. 1994; Nowotny et al. 2003) and Post-Normal Science (Funtowicz and Ravetz 1993). Instead of attempting to establish the legitimacy of different knowledge claims, all perspectives are considered legitimate and the focus shifts to the quality of the

scientific process. Hence, Mode 2 science focuses of the accountability and transparency of the scientific process. Accountability is understood as institutionalised responsibility and is part of a re-definition of the roles and boundaries between science and society (Gibbons and Nowotny 2001). Gibbons and Nowotny (2001) argue that not only the context of application of science has to be taken into account, but also the context of implication, thus paying attention to the social robustness of the scientific information produced.

Post-Normal Science draws attention to the level of uncertainty and to the stakes involved as a way to adapt scientific practices to each situation. Thus, normal science, defined as puzzle-solving exercises, operates in the field of reducible uncertainty. Adequate training provides the expert with the competence, and therefore the legitimacy, to solve the problem. Examples are the knowledge required by an engineer to design a bridge, by a plumber to fix a water pipe, by a math student to solve a differential equation. As uncertainty increases, professional consultancy is seen as a more appropriate practice. In the case of surgery, for example, patients are most likely to ask for a second medical opinion before submitting themselves to a risky treatment – not because the competence of the first doctor is questioned, but because the complexity of the problem may imply the existence of different solutions depending on the specific point of view adopted when framing the issue (Funtowicz and Ravetz 1993). Finally, in a situation of irreducible uncertainty, Funtowicz and Ravetz speak of post-normal science. In this case, "extended peer review" is advocated in order to take into account different points of view in the pursuit of quality (O'Connor 1999).

2.2 Pluralism and Governance

The existence of a plurality of perspectives poses serious challenges to the science-policy interface. I refer to governance in order to situate the concept of "science for policy" in the context of pluralism. Kooiman (1999) identifies ten different uses of the term governance in a variety of different context and purposes. He goes on to argue that the term has gained such popularity due to the increased recognition of the interdependencies between a plurality of social actors, including the state, civil society, the private sector and the scientific community. Without choosing any specific definition, in this dissertation I refer to governance as the wide umbrella for the study of a variety of policy and decision-making processes in the context of high uncertainty and complexity.

The science-policy interface can be characterised in a variety of different ways. Funtowicz and Strand (2007) identify 5 models of science and policy, based on different ways in which science is used to inform policy. Those are the modern model (science speaking truth to power), the precautionary model (precaution as the strategy to deal with uncertainty), the framing model (politics are recognised as taking part of the problem framing), the demarcation model (good science is seen as separate from politics) and the model of extended participation. The first four models are based on the conception of science speaking with one voice. Only the latter explicitly deals with pluralism.

In this dissertation, I take a slightly different perspective and I analyse models of science and governance from the point of view of pluralism. I identify three approaches to the governance of the science-policy interface in the context of pluralism, namely the (i) view of science speaking consensus to power, (ii) working deliberatively within imperfection (van der Sluijs 2010) and (iii) reflexive governance. The first two approaches are characterised by different positions on how to deal with pluralism and the possibility of reconciliation from the science-policy interface perspective, while the third approach is a reflection on how pluralism affects the way science and policy interact. I analyse the three approaches in turn.

The first approach to pluralism is defined as science speaking consensus to power. The concept of consensus is based on what O'Connor (1999) identifies as the Laplacian perspective on reconciliation, which seeks reconciliation through "a single and internally consistent conceptual framework" (Ibid: 672). The Laplacian view resonates with Neurath's insistence on the need for an orchestration between different disciplines in order to achieve a more complete description of reality.

This perspective can also be found in the ideal of deliberative democracy. Brown (2009) defines deliberative democracy as a way of taming pluralism through dialogue following the Habermasian view of communication. Habermas' work on modernity and communicative action is based on an ideal community, rather than on empirical work, in order to construct a theory of "unconstrained mutual understanding among individuals" (Habermas 1989: 2). According to this view, differences can be reconciled through communication.

Within this perspective, the science-policy interface is based on the ideal of seeking consensus and reducing the plurality of worldviews to one single view. The presence of pluralism does not fundamentally alter the relationship between science and policy. In this interpretation, pluralism is a temporary obstacle that can be dealt with through communication. Pluralism is tamed by processes of reconciliation within science, which make it possible for science to speak to power. The existence of non-equivalent worldviews implies a move away from the view of science as describing reality as it is towards that of science as the locus for consensus among different worldviews.

The second approach to pluralism is defined as working deliberatively within imperfection. In this case, the possibility of reconciliation is questioned. O'Connor (1999) speaks of dialogical perspective, which looks for a coexistence of irreducible pluralities. The dialogical view of reconciliation is more in line with the notion of incommensurable worldviews proposed by Munda (2005a), which has deeper implications than that of expressing different points of view. In other words, different worldviews are not necessarily complementary and not always compatible with each other.

High levels of uncertainty, which can be seen as imperfections of knowledge, imply that different disciplines may not advance towards a full unity of knowledge (Douguet et al. 2009). This implies that the orchestration of sciences called forth by Neurath is not so easy to achieve, independently of the use of scientific methods and independently of the transparency of the process of production of scientific information. As Strand and Cañellas-Boltà point out, it is important to reflect upon which "lines of action will be underestimated, discredited or forgotten" by the consideration of a plurality of legitimate perspectives (2006: 203).

The dialogical view can also be associated with Rhodes' (2007) concept of differentiated polity. Rhodes argues that differentiation within the British government has led to a multiplication of networks with a high degree of interdependence, reducing the capacity of the core executive to steer. Pluralism in this case leads to a redefinition of democracy itself. A similar concept is put forward by Brown's (2009) idea of agonistic democracy, which sees controversies as irreducible and calls for a reconceptualisation of democracy itself.

In this context, the science-policy interface is also challenged. In the postmodernist school, the relationship between science and policy is deconstructed as a criticism to the very idea of dialogue between science and other spheres of governance. Lyotard (1979) suggests the concept of paralogy, defined as the movement against the establishment of a certain narrative, as a way of testing the legitimacy of the knowledge claims used to inform policy. Lyotard's critique of modernity (and of Habermas) rejects the idea of communicative rationality on the grounds of scepticism towards the ability of communication to go beyond language games. Irreducible uncertainty leads to "the perspective of mobilising incomplete knowledge and exploring considerations of pertinence of knowledge as a function of context" (Douguet et al. 2009: 43).

The question of pertinence of knowledge leads to the third approach to science and policy in the context of pluralism, which is based on reflexivity. In this case, pluralism is not something to be governed, but rather the starting point to analyse the science-policy interface. The third approach consists of Voss and colleagues' (2006) reflexive governance, which deals the "specific dimensions of problem handling such as analysis, goal definition, assessment or strategy implementation" (Voss et al. 2006: 7). Pluralism of problem framings and policy recommendations leads to a critical reconsideration of the way science for policy is produced and of the governance processes in place. Thus the goal is no longer that of dealing with pluralism, but rather pluralism creates the necessity of reviewing the science-policy interface. The assessment of the science-policy interface is carried out through reflexivity, that is, the analysis of one's own assumptions, goals and course of action.

The concept of reflexivity in reflexive governance is used to refer to the assessment of the science-policy interface, and can be associated with the notion of reflexivity used by Beck and colleagues (1994) in reflexive modernisation. Beck and colleagues argue that modernisation leads to a breakdown of traditional values, institutions, personal identities and also challenges the science-policy interface. In this context, science is faced more and more with risk, uncertainty and complexity, leading to a reflexive assessment of its own practices. The third approach can be understood as a further development of the assessment of science for policy as a function of context, which leads to an assessment of the quality assessment (Douguet et al. 2009). Reflexivity about the practices of governance leads to a redefinition of those practices, which Voss and colleagues define as second-order reflexivity.

Reflexive modernity also arises as a critique to the deconstructionism of postmodernity (Beck et al. 1994). Reflexivity is taken as a means to reconstruct the relationship between science, policy and society. The main difference between reflexive governance and the previous approaches is that latter is not concerned with reconciliation and with the implications of pluralism for democracy and for scientific knowledge, but rather with the way scientific practices are affected by pluralism. There is a shift from epistemological pluralism as the basis for action, towards knowledge about uncertainty as the basis for renewing the science-policy interface (Beck et al. 2003).

In practice, instance of all three models can be found depending on the context and on the issues at stake. This dissertation contributes both to the "working within imperfection" and to the reflexive governance approach. The quality assessment of scientific representations used for governance based on pertinence and usefulness consists of a reflexive analysis of one's own pre-analytical choices.

However, it should be noted that reflexivity is not a quick fix to deal with controversies. In this sense, the approach developed in this dissertation has a more modest aim than that of redefining governance through reflexivity. Reflexivity should rather be understood as a martial art (Bourdieu and Wacquant 1992), that is, a set of analytical tools that make it possible to shed light over the sources of controversy based on the analysis of the motivations, beliefs and social context of different observers. Bourdieu refers to martial arts in as far as these analytical tools serve to enhance understanding rather than as a tool for active intervention in the world.

2.3 The disciplinary context

This dissertation is an investigation of the epistemology and methodology of sustainability science and its use for governance. This section relates sustainability science to the debates in philosophy of science introduced above. More specifically, I comment on how sustainability science relates to pluralism and the duality between value-free and value-laden scientific information.

Sustainability science is at the cross roads between the views of ecology on the environment, economics on the management of productive activities and sociology relating to equity, justice, human rights, social capital, and so on. Sustainability science emerged from the debates about sustainable development in the 1980s and 1990s. In particular, the lost decade of development of the 1980s flagged the need for more coordination and interchange between the different disciplines studying sustainability issues. The term sustainability science emerged only later to indicate a set of sustainability problems that are addressed from a variety of disciplines (Kates et al. 2001), rather than a new discipline.

According to Kates and colleagues (2001), sustainability problems are characterised by the presence of multiple spatial and temporal scales, urgency, complexity and pluralism. Sustainability science deals with a plurality of perspectives on the socio-economic process and its relation to human wellbeing and the environment. This relation can be analysed both in the short term (seen as end-means individual utility maximisation in economic terms), and in the long term (taking into account the interactions with, and degradation of, the ecosystem at a global scale). A plurality of worldviews is one of the characteristic features of sustainability.

Many tensions arise from the use of different disciplines in sustainability science. For example, Goodland and Daly (1996) distinguish between weak sustainability and strong sustainability in order to illustrate how different approaches are combined in different representations of the system and evaluations of the problem. Weak sustainability is defined as maintaining the total capital, as defined within an economic narrative assuming the possibility of substitution among different forms of capital, regardless of their characteristics (natural, human-made, social or human). Strong sustainability is defined as maintaining the different types of capital separately, assuming that perfect substitution among different forms of capital is impossible. This difference reflects the contrast between the economic narrative of perfect substitution based on monetary valuations and the biophysical narrative associated with the consideration of the function of a specific resource or species within the ecosystem.

These two perspectives of sustainability have different implications in terms of how to reconcile different disciplines within sustainability science. For example, contradictions emerge between the economic imperative of maximising efficiency and the ecological view of robustness as moderation. Ulanowicz and colleagues (2009) warn that maximising efficiency may lead the system to reduce its reserves and, consequently, reduce its capacity to adapt to changes in external conditions, such as resource depletion. On the other hand, maximising efficiency is seen as a requirement for economic growth from a neo-classical perspective.

Warnings about the depletion of natural resources were published by the Club of Rome in 1972, with the book *The Limits to Growth* (Meadows et al. 1972). Such pessimistic forecasts sparked a controversy between what came to be known as the "Prophets of Doom," warning about the imminent collapse of society and of the ecosystem, and the "Cornucopians," proclaiming that human ingenuity and technological innovation would arise to solve such issues (Giampietro et al. 2012; Porter 1995). One example of the latter attitude is given by the claim that alternative energy sources will be discovered as fossil fuels become scarcer (Porter 1995).

Sustainability science is fragmented into a variety of different approaches and perspectives, and it does not indicate a defined methodology or set of methodologies. I refer to sustainability science in this dissertation in order to analyse the umbrella of disciplines that study sustainability issues, and to compare methodologies and epistemological stands of the disciplines that enter each case study.

The different disciplines used in sustainability science have very different approaches to the normative aspect of representations of the world. For example, environmental aspects are often taken as facts, while the social dimension is identified with values. In neo-classical economic analysis, values are reduced to the agent's expression of personal preferences in their interactions with the market. The representation of the economic process, however, refers to an abstract economic agent whose behaviour is captured by statistical aggregates, and thus the representation is considered to be value-free.

Ecological economics, on the other hand, is based on the consideration that different values are not reducible to each other and cannot be expressed in monetary terms (Martinez-Alier et al. 1998). Ecological economics can be seen as a critique to the weak sustainability approach of environmental economics, and as an attempt to reconcile economics with pluralism.

The reference to value-laden representations in this dissertation points to the fact that values are assumed to play a role not only in the actor's behaviour but also in the choice of observation and of analytical tools. I carry out a reflexive examination within sustainability science of the representations and methodologies used to deal with sustainability issues, including the pragmatic aspect. This approach follows Bourdieu and Wacquant's (1992) invitation to transcend the false antinomy between objectivism (the quest for truth) and subjectivism (the focus on values) and to look at how the two interact with each other. The fact that representations of the world are necessarily value-laden does not mean that they should be considered non-scientific but rather that they should be evaluated according to their fitness for purpose. The insistence on purpose indicates that scientific information does not exist in a social vacuum (Merton 1938) or as a view from nowhere (Nagel 1989).

3. Framework of the research[1]

This section introduces the theoretical framework used to analyse scientific representations in this dissertation. I use Rosen's modelling relation, hierarchy theory and semiotics in order to represent the existence of a plurality of legitimate perspectives within sustainability science. This framework makes it possible to identify the pre-analytical choices of the relevant attributes to be observed and the consequences of these choices for action. The focus on pre-analytical choices contributes to the practice of reflexivity in quality assessment.

In relation to the debates touched upon in the previous section, the focus on pre-analytical choices leads to the analysis of the cognitive process. According to this framework of analysis, the decision of what to observe is based on the observer's goals and values, which act as a filter between the observer and the external world (Rosen 1985; Ahl and Allen 1996; Maturana and Varela 1980; Von Uexkull 1926). This framework does not specify whether the observer is a specific individual or a typology of observer.

A markedly different point of view is offered by sociology. Elias goes to great lengths in explaining the complex relationship that exists between the individual and society, as "the attributes and the behaviour of systems on different levels and above all those of the paramount system itself cannot be described simply in terms appropriate to those of their parts; nor can they be explained as effects of which their constituents are the cause" (1956: 250). Elias stresses the complexity of the relations between the individual and the social, pointing at the fact that the cognitive experience cannot be explained by considering only one of the two. Bourdieu further explores the concept of regularities that emerge from the complex interactions between the individual and the society in his work on reflexive sociology (Bourdieu and Wacquant 1992).

In the modelling relation, the observer is always a socially constructed typology of observer and this assumption is taken to explain the unavoidable presence of a

[1] This section has been adapted from Kovacic and Giampietro (2015).

systemic bias in what is observed and in the results of the observation. However, the process through which the observer is influenced by society is not studied.

I am aware of the limited explanatory power that the framework chosen for this dissertation has with respect to the social, political and cultural context in which the representations analysed are generated. Nonetheless, too narrow a focus on the power struggles within science runs the risk of blinding the analysis with respect to the biophysical constraints and the associated epistemological challenges posed by uncertainty and complexity in relation to environmental issues. Given that my focus is on the science-policy interface of sustainability issues, I find the use of approaches presented below useful. For an investigation of how the understanding and study of sustainability issues evolved along with the philosophy of science, environmental sociology (Lemkov 2002) is a more pertinent approach.

In section 3.1, I provide a description of the process of production of scientific representations, based on Rosen's modelling relation. Particular attention is paid to the pre-analytical choices determining what is observed and how. In section 3.2, I introduce the concept of pluralism and provide a representation of epistemological complexity based on the modelling relation. In section 3.3, I turn to the issue of how scientific representations are used in governance and introduce the concept of narrative as a key analytical tool.

3.1 The implications of Rosen's modelling relation

Returning to reflexivity, Elias asserts that "we must constantly reflect not only on the observations we make on the empirical level, but also on the forms of thinking we use to cope with what we observe" (Elias 2013: 160). This reflection calls for an analysis of both the observations one makes and of the process of observing. The assessment includes the consideration of the role of the analyst and of their *modus operandi*. The scientist should "avoid treating as an instrument of knowledge what ought to be the object of knowledge" (Bourdieu and Wacquant 1992: 247). Bourdieu argues that one should submit to scientific scrutiny all the beliefs that make such experience of the world possible. As a matter of fact, since experience is conditioned by beliefs, Bourdieu speaks of “doxic experience” (1992: 247). Reflexivity also requires that the social context and norms within which the observer acts and which influence their goals and beliefs, also become the object of study.

Reflexivity in this dissertation is limited to the assessment of the role of pre-analytical choices in determining what to observe and how. I do not talk about the role of social norms in determining one’s view of the world, or about the effect of individual perspectives on social norms. This choice responds to the aim of investigating the intersection between the descriptive and the normative aspects of scientific representations, rather than explaining the origins and effects of such choices. For this reason, I refer to the description of the observation process provided by the theoretical ecologist Robert Rosen.

Adopting this point of view, it is possible to assert that one’s perception of the external world and their interpretation of the resulting experience reflects their beliefs about what is relevant. When observing nature, the observer does not know the laws governing it; they can only infer them from their observations. As a consequence, the inferred laws may change according to either the point of view adopted and/or the experience accumulated. The sun did not revolve around the earth before Copernicus' findings; the new observation is due entirely to the adoption of a different narrative or set of beliefs.

The distinction suggested by Pattee between rules and laws helps distinguish between the observer and the observed system. Laws are universal and inexorable, dynamic, rate-dependent *processes* that are generated by the observed system. Rules are linguistic, local, rate-independent *descriptions* that are generated by the observer (Pattee 1977, 1978). Rules are the result of the observer's decision to observe in a certain way (Ahl and Allen 1996).

The distinction between the observer and the observed system (or, better, the perception of the observed system) is used in order to explain pluralism, rather than to assert that so-called reality can be described in abstraction from the observer. Boyle used a similar argument, for example, in order to show how objective knowledge can be produced through empiricism (Shapin and Schaffer 1985). In this dissertation, the distinction between observer and observed system should be understood as an analytical tool used to describe the cognitive process rather than as a description of some ontological condition.

The rules defined by different disciplines (for example, economics, thermodynamics, psychology) are used to construct models about the observed system (homo economicus, steam engines, behavioural and cognitive patterns), as a way to infer the dynamic laws that govern that system. Rules are "epistemological concepts of measurement" (Pattee 2007: 117) used to describe laws. The choice of a given discipline entails a very specific definition of rules, such as the scale of analysis, the relevant attributes and the causal relations between the observed attributes. The totality of these choices constitutes the *descriptive domain* used by the observer to observe the system.

Rosen takes a step further and describes the process through which human beings code the signals coming from the observed system. Rosen (1985) defines a model as the formalisation (representation in a given descriptive domain) of the perception of a particular observed system (belonging to a known typology) by a specific typology of observer. I refer to Rosen's modelling relation (figure 1) to better clarify this point and in order to explain how representations are built from perceptions (for a more detailed discussion see Mayumi and Giampietro 2006; Giampietro et al. 2006; and Chapter 4 of Giampietro et al. 2012). This analysis takes perception as a given, in abstraction from the social context of the analyst, and therefore should not be considered as an alternative or a substitute for sociological analysis. This approach is useful in studying the epistemology of sustainability science.

A model starts with the perception associated with a tentative explanation of causality over a given change of states. What has to be observed is perceived through an expected set of attributes associated to its identity. The observed system must be a special instance of a known type (an equivalence class of the observed system – for example, a salmon can be considered as an instance of an equivalent class of fish belonging to family of Salmonidae) defined as relevant within a given narrative. The type is assumed to be in *good relations* with its context (the interactions with higher level components are supposed to take place in favourable boundary conditions – a fish can only live in water) and *problem-free* in relation to internal processes (the interactions among lower level components is supposed to guarantee the functioning of it – a fish knows how to swim and it can swim). After having imposed this heavy set of assumptions, the observer can define tentative explanations about the behaviour of the observed system (explaining changes in states). This pre-analytical hypothesis, or belief, about *what the observer expects to observe* – represented in Figure 1 as arrow 1 – is at the core of the modelling relation.

The second step consists in encoding the relevant attributes of the observed system, that is, the observing and measuring the qualities of the instance of the system perceived as relevant. The choice of *what* to observe and *how* operates as a compression (or simplification) of the possible encodings of the observed system. A full catalogue of the external world would make data “as unmanageable as the material externality” (Zellmer et al. 2006: 173). Only the relevant variables are considered in the model reflecting the choice of a manageable set of observables that can be described through coding.

The third step consists of the construction of a formal system (the model) representing the observed system and used to make inferences about the behaviour of the latter. The construction of a model is a process of idealisation about the functioning of the observed system (Chu 2013). Hence, inferences are the formalisation of the idealised causal relations attributed to the observed system in the pre-analytical phase.

The fourth step is the decoding of the relations established in the model in order to make predictions about the behaviour of the observed system. The decoding tests the consistency between the perception of causality over changes of states of the observed system (the arrow 1 in the figure) and the results of the anticipatory model provided by the formal system (the combination of the arrows 2, 3, and 4).

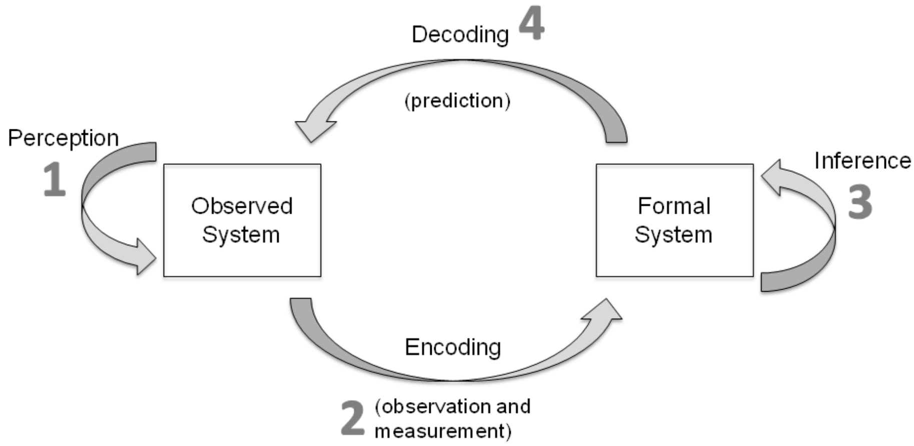

Figure 1. Rosen's modelling relation. Source: Kovacic and Giampietro 2015.

Following Rosen's description, models can be defined as the formalization of the observer's beliefs about the external world, which are determined by the discipline of reference, affected by the social and cultural context, by the work of other scientists in the field, *et cetera*. Put in a different way, beliefs and values not only influence the model but are necessary for its construction. For instance, the use of GDP requires the analyst to choose the scale of analysis (national level), the descriptive domain (economics), and the appropriate observation scheme (measuring production), all of which are normative choices. The model is validated if the formal representation proves useful in explaining the observed behaviour of the system, that is, if the semantic framework set by the model (measuring productive activities) is consistent with the chosen narrative (economic growth increases welfare).

It should be noted that any given representation of the observed system is not meaningful outside of its corresponding narrative. For example, the characterization of marginal utility of a good or service is meaningless outside of an economic model of consumer behaviour, and gives no useful information to a biologist in describing the structure or evolution of human beings. In the same way, a model describing the behaviour of a given species of fish gives no useful information if a specimen of that species is lying on a kitchen table. The definition of relevance of the narrative, in turn, depends on the social context within which the analyst is operating.

3.2 Plurality of perceptions

The modelling relation makes it possible to see how quantitative information is the result of the decision of how to observe the world. The observation in turn depends on the specific narratives associated with the disciplinary knowledge used and determining the position of the observer and the scale of observation. For example, ecologists observe the evolution of ecosystems over hundreds of years, economists observe the performance of the economy over one year, physicists may observe the behaviour of atoms over a nanosecond. In this context, different representations of the same observed system are not the result of conflicting opinions about the observed system, but the consequence of different choices of how to observe the system.

The co-existence of a plurality of perceptions of the observed system requiring the adoption of different scales of analysis implies the creation of non-equivalent descriptions of the system (Figure 2). This is also known as epistemological incommensurability (Munda 2004): the same system can be modelled as different representations that are non-equivalent and non-reducible to each other. Two descriptive domains are non-equivalent if it is impossible to reduce their representations of metrical relations (perception of space) and temporal relations (perception of time) to each other without losing relevant information (Giampietro et al. 2014).

As a consequence, when using multiple non-equivalent descriptive domains, a given system will be described by sets of observable attributes, variables and parameters that are logically incoherent: they cannot be reduced to a single model. This is the challenge faced by composite indicators: happiness, economic performance and soil erosion cannot be captured by the same metrics. This incommensurability of values is at the core of the discussion over the issue of how to aggregate and weight non-equivalent attributes (Saltelli et al. 2009).

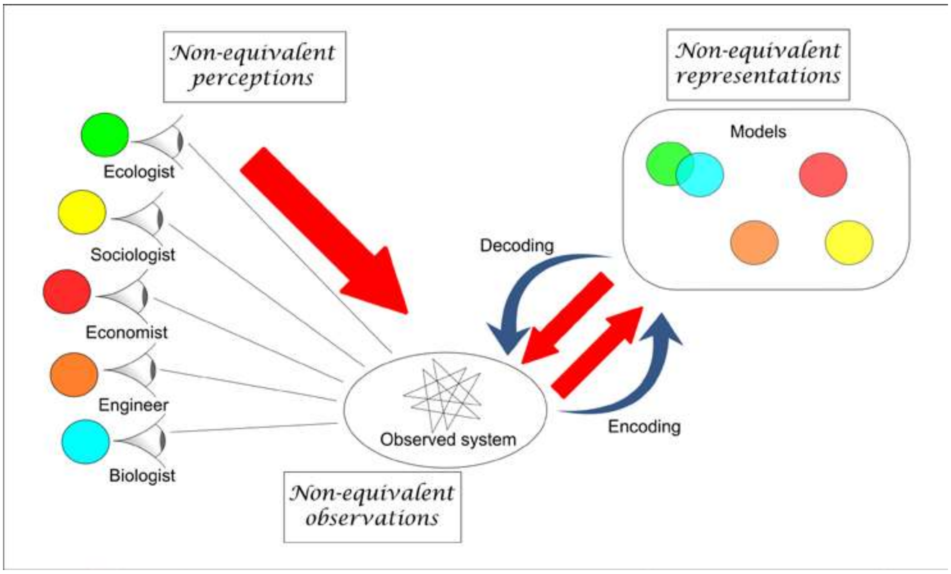

Figure 2. The existence of non-equivalent perceptions and non-equivalent representations of the same observed system. Own elaboration, adapted from Zellmer et al. 2006.

The existence of a plurality of non-equivalent representations poses an important challenge to the use of scientific information for governance, as discussed in section 2.2. Although this dissertation does not engage with the question of whether contradictions can be reconciled or not through communication, this debate highlights the need for a more thorough study of the incommensurability and inconsistencies between different representations as a way to shed light over the challenges of the science-policy interface.

3.3 The role of narratives in the semiotic process

This section relates the issue of epistemological pluralism to the use of scientific information for policy. In order to establish a link between the plurality of non-equivalent representations described in the previous sections and the use of those representations for policy, the approach of semiotics is introduced. Once again, semiotics overlooks the broader social and political processes within which the individual is acting, but is useful to establish a link between the epistemological analysis of scientific information and its use for guiding action.

Semiotics is the scientific field that studies signs and sign processes. Semiotics makes it possible to assess the usefulness of semantics (the meaning of signs) and the usefulness of syntax (the formal structures of signs, such as data and mathematical models). Formal signs (symbols) can be considered as compressed pieces of information, capable of signifying something for the interpreter of the sign. If one considers a model as a structure of signs, semiotics can shed light over the process of knowledge creation by providing a link between the pre-analytical step of defining a narrative (and its relative perception) and the *application* of the model. Semiotics deals with the effective combination of three interfaces:

1. Semantics: the step of "transducing" the information (meaning) associated with symbols. Transducing refers to the different uses of symbols in the process;
2. Syntax: the step of "representing" the formal relations between symbols, that is, the production of any formal system of inference based on proxy variables and data;
3. Pragmatics: the step of "applying", that is, interacting with the external system both when observing and when taking action.

The three steps can be associated with the encoding (transduce in order to encode – moving from arrow 1 to arrow 2), modelling (represent arrow 3) and decoding (transduce in order to apply – moving from arrow 4 to informed action) steps of Rosen's modelling relation. In this sense, the semiotic process can be seen as the process of production of representations of the observed system based on the chosen perception of what the system is, leading to a specific choice of encoding variables and descriptive domain, needed to generate anticipatory models used to guide action. As new experience is generated through applications of the model, perception is updated generating new representations.

The concept of semiotic triadic relation, introduced by Peirce (1935), refers to the process through which useful representations are continuously selected and validated through interactions with the external world. Peirce envisioned the process of formation of representations of the world as an endless iterative process based on the three steps (described using verbs):

→ *semantic (transduce)* → *syntax (represent)* → *pragmatic (apply)* →

Semiotics makes it possible to take a step further and study the usefulness of models in guiding action, thus shifting the focus from the model as a representation to the model as a tool for interaction with the world.

In order to reconcile the focus on the individual with the social, cultural and historical context in which the individual acts, Giampietro and colleagues (2006) introduce the concept of narrative referring to the choice of relevant relations of causality. Narratives play a crucial role in the governance of pluralism. Narratives are a way of making sense of a plurality of heterogeneous perceptions. Narratives represent “an act of interpretation which gives meaning to a sequence of actions” (Magrini 1995), a way of ordering experiences and observations (Phillips 2014). Narratives can be considered as the cultural glue making commensurate experience about a plurality of interactions with the external world possible in a given society (Allen and Giampietro 2006). In this sense, narratives create knowledge through story-telling (Lyotard 1979).

The introduction of the concept of narrative is a way of taking into account the social context within which individuals act, linking the cognitive process of the individual to the formation of knowledge at the social level. Narratives help create a common interpretation of the private experiences of individuals but overlook the complex interactions between the individual and society. That is, narratives play a role in the definition of the beliefs but are also influenced by the beliefs of different actors, by power relations and social dynamics. It should also be noted that narratives evolve over time and therefore the analysis of existing narratives only reflects a snap-shot picture of the current system of beliefs. This leaves out the understanding of how the relation between society and the individual changes over time. This approach does not provide an analysis of the interactions between society and the individual.

For the purposes of this dissertation, I use Lyotard's concept of narrative, which refers to the "pragmatic aspect of utterances" used to legitimise scientific knowledge (Lyotard 1979: 9). The focus on narratives is compatible with the analysis of representations and is not meant as a comprehensive analysis of social practices (Habermas 1989) or of discourses and the relationship between knowledge and power (Foucault 1979). The concept of narrative refers to the statements used and makes it possible to study the intersection between science and policy.

The choice of narrative is essential for the construction of anticipatory models. Anticipatory models are used to guide action and, in the context of human societies, anticipatory models are useful tools in guiding policy. A model of development based on GDP indicators may be useful in guiding decision-making in the short run. On a larger time scale, when looking at centuries, an ecological model taking into consideration the consequences of environmental pollution, resource depletion (particularly fossil fuels) and demographic variables may be a more useful guide in pointing out the bottlenecks of a given development strategy. The choice of narrative is thus far from a purely theoretical concern, as it has a direct impact on the governance of social and ecosystems.

According to the framework presented in this section, reflexivity requires the observer to identify the narrative within which they are operating. In the epistemological definition of quality assessment, the validation of the model refers only to the congruence between the specific model (arrows 2-3-4 in the modelling relation) and its related narrative (arrow 1). For the modeller, the starting narrative is assumed to be relevant and useful by default (otherwise the modeller would not bother making the model). Reflexivity requires an additional the assessment of the usefulness of the chosen narrative, which I have classified as a pragmatic quality assessment in relation to the purpose of the analysis.

The focus on narratives makes it possible to address the following set of questions: Who decides that the chosen narrative is "the" relevant narrative to be used for generating the required information? What if there are several relevant non-equivalent narratives that have to be considered simultaneously? What if there are legitimate but contrasting claims about the relevant narratives that should be used for dealing with a given issue? In relation to what is "relevant" being defined? Whose point of view is being considered? Who is being left out of the debate?

4. Research objectives

I will now provide a brief summary of the motivation for this research, the debates addressed and the theoretical framework adopted in order to define the research questions.

The motivation for this dissertation is both practical and theoretical: on one hand, there is a need for a better understanding of science-policy issues that are not well-governed, that are characterised by a poor understanding of uncertainty and complexity, by lack of dialogue and that are addressed through terrible simplifiers. In relation to this practical need and on a more theoretical level, the purpose of this dissertation is to contribute to the understanding of how scientific knowledge of complex sustainability issues is mobilised at the science-policy interface.

In the context of irreducible uncertainty, the concept of quality does not refer to a substantial evaluation of the quality of scientific information, but rather to a pragmatic and epistemological quality assessment of scientific representations used for governance. I address this challenge by applying the theoretical concepts of complexity theory to the quality assessment of scientific representations of sustainability issues used for governance.

The research objective can be unpacked into two main research questions:

1. How do the concepts of pertinence and usefulness for the quality assessment of the scientific representations of sustainability issues unfold in practice?

2. How does the multi-scale approach contribute to the understanding of complexity in science-policy issues?

With these questions in mind, the general research objective can be broken down in the following objectives, related to the three case studies:

1. Analyse the relation between the mono-scale neo-classical economics knowledge base and the complexity of the 2007-08 financial crisis.

2. Analyse the set of competing scientific representations and competing policy agendas for water management in Israel from multiple scale of analysis.

3. Analyse the relation between scientific representations of smart grids and the future visions of smart grids promoted by the European Commission in terms of pertinence and usefulness.

5. Approach

This section describes the conceptual and analytical tools used to answer the research questions. I give an overview of complexity theory and of the approach I developed based on it. A more detailed description of the specific methods used in the case studies is provided in the following chapters. In section 5.1, I introduce complexity theory and the approach I developed. Section 5.2 describes the multi-scale approach and how the concepts of usefulness and pertinence are used for the quality assessment of scientific representations of sustainability issues. In section 5.3, I give an overview of other approaches to the quality assessment of science for policy, namely NUSAP, Knowledge Assessment Methodologies and Sensitivity Auditing. I compare and contrast the multi-scale approach used in this dissertation to the other methods, highlighting the contribution of the multi-scale approach. Section 5.4 closes with an assessment of the limitations of the multi-scale approach.

5.1 Complexity theory based approach

I refer to complexity in this dissertation as both a way of representing the issues analysed and as a conceptual tool used to analyse the plurality of representations of a given issue. When defining the research problem as the challenge of dealing with uncertainty and complexity, I refer to complexity as the existence of an open set of non-equivalent perceptions about the system under analysis. At the same time, I use complexity theory as the lenses through which to analyse how knowledge is mobilised at the science-policy interface. In order to clarify this double use of the concept of complexity, I will introduce first what is meant by complexity in this dissertation and then proceed to explain how different concepts from complexity theory are used as analytical tools in order to answer the research question.

Complexity can be defined in many different ways (for an overview see Funtowicz and Ravetz 1994b; Strand 2002). I refer to the definition used in hierarchy theory, based on the work of Koestler (1967), Simon (1962) and Prigogine (1986). Simon defines a complex system as a system “made up of a large number of parts that interact in a non-simple way” (1962: 468), where the identity of the whole is different from the sum of the parts, due to what Prigogine (1986) calls emergent properties of the whole.

For example, different roles and interactions between 5 individuals determine whether the whole is defined as a family or as a basketball team. Neither a family nor a basketball team can be fully described by considering only the number of components, or by considering the roles of the individuals (son or forward player) in isolation. Complex systems require the consideration of multiple scales of analysis in order to be able to identify the functional and structural properties of the parts that determine the identity of the overall system (how the members of the family or the basketball team interact according to expected rules), as well as how the emergent properties of the overall system determine the function of the parts (how the performance of the household or the basketball team implies different roles for different members).

According to this definition, a problem is complex when its definition requires the simultaneous consideration of multiple scales of analysis (for example, the interactions of the parts inside the black-box and the interaction of the black-box with its context). Sustainability issues are necessarily complex, as they entail the management of the present (local scale) in relation to a desired future state (large scale). In order to deal with non-equivalent perceptions of the same system, Koestler (1967) introduces the concept of *holon*, indicating an entity that is both a part and a whole.

The *holon* is a conceptual tool that makes it possible to deal with the epistemological duality of describing a system both from the internal view and from the external view (Allen and Giampietro 2014). For example, food can be described from the internal view in terms of proteins, carbohydrates and fats, and from the external view in terms of vegetables, cereals and meat. The two descriptions are non-equivalent, they respond to different functions at different levels of analysis, and yet both are valid descriptions of food.

The duality entailed by the concept of *holon* makes it possible to distinguish between structural and functional types at different levels of analysis (Allen and Giampietro 2014). As explained in the first case study, at the level of the economy, financial institutions represent a structural type – they are institutions guaranteeing the circulation of money in the economy – while at the level of individual economic agents, financial institutions represent a functional type – they act as rational profit maximising firms.

The analysis of complex system requires the use of multiple scales of analysis. The approach developed in this dissertation is based on the definition of complexity given above and on the conceptual tools provided by hierarchy theory. The consideration of the interactions between the whole and the parts has consequences not only in terms of the representation of the system but also in terms of the interactions between different representations. Hierarchy theory is thus useful in addressing the issue of pluralism.

In this respect, Funtowicz and Ravetz (1994b) distinguish between ordinary complexity and emergent complexity. Ordinary complexity stops at the consideration of the existence of a diversity of elements and subsystems. Emergent complexity looks at the autocatalytic processes implied by the interactions between the parts and the whole. More to the point, emergent complexity is about contradiction, defined in dialectical terms as "the coexistence of antagonistic forces, [which] provides a perspective which prevents oversimplified analyses of solutions and problems" (Funtowicz and Ravetz 1994b: 572). Following the definition of emergent complexity, the conceptual tools of complexity theory in this dissertation are used not only to provide a representation of the system but also to highlight the contradictions that emerge between different representations.

Ordinary complexity leads to the production of yet another description of the observed system, that is, a more complex description. Pilkey and Pilkey-Jarvis (2009) criticise this use of complexity as the new panacea for dealing with failed predictions – the answer is to expand the boundaries of the systems and to take into account feedback loops and non-linearity. However, the same level of epistemological simplification is often maintained when increasing the complicatedness of the representation. Ordinary complexity reduces uncertainty to a question of problem framing. Emergent complexity calls for reflexivity, for the recognition of the role of the observer in the definition of the system. A similar distinction is made by Strand (2002) through the concepts of thin and thick complexity.

I use complexity theory as a tool, as a method of analysis, and not as a means of reducing uncertainty. In this case, to increase the complexity of the description is to take into account a wider variety of perceptions, values and worldviews. The existence of a plurality of perceptions makes the very formulation of the problem uncertain. In this sense, the emergent complexity view is more suited to deal with indeterminacy. As a consequence, attention to emergent or thick complexity leads to "messy governance" (Strand and Cañellas-Boltà 2006) rather than to a better definition of the observed system.

In this context, the consideration that sustainability issues are complex does not only mean that multiple descriptions of the issue should be provided from multiple perspectives, but also that the contradictions that emerge from these multiple non-equivalent representations should be an integral part of the analysis. At the same time, the existence of non-equivalent representations of sustainability issues confirms the importance of normative choices in the production of any description of the world, resulting in different choices of narrative, of scale of analysis, of causality relations attributed to the observed system, and so on.

Ahl and Allen suggest using hierarchy theory as "the theory of the observer's role in any formal study of complex systems" (1996: 29). Recalling on the discussion about simplification from section 1, section 3 has shown how simplification, defined as the production of formal models as an idealisation of the observed system, is necessary in policy-making. Models are used for guiding action in the semiotic process. Under this light, the question of fitness for purpose can be unpacked into two sets of pre-analytical choices: (1) the definition of purpose, answering the *why* question, and (2) the choice of *what* to observe and *how*. These two steps are described by Zellmer and colleagues (2006) as two successive compressions. The first compression is a selection of the useful narratives about what the narrator considers relevant among all the perceptions and worldviews available. The second compression is the selection of the pertinent representation among all the possible models and methods available.

The two compressions deal with different levels of uncertainty. The first compression refers to the problem framing, it answers the question of *why* something should be studied in the first place. The challenge of the first compression is to face indeterminacy and ignorance, which cannot always be dealt with through existing methods or disciplines because these high levels of uncertainty flag the limits of existing knowledge. The second compression refers to the choice of method, answering the question of *what* to represent and *how*. The second compression has to do with lower levels of uncertainty, related to methodological and technical issues. Thus the framing provided by hierarchy theory makes it possible to highlight how representations of complex sustainability issues entail both a choice of problem definition and one of scale of analysis.

5.2 Conceptual and analytical tools

Having defined complexity theory as the perspective from which I analyse how knowledge about sustainability issues is used for governance, I now specify the concepts used to carry out the analysis. In order to provide a systematic characterisation of the multiple perspectives from which complex systems can be described, I use the concept of scale. Multi-scale analysis is part of the Multi-Scale Assessment of Societal and Ecosystem Metabolism (MuSIASEM) approach, developed by Giampietro and Mayumi (2000a; 2000b; for a full description of the approach, see Giampietro et al. 2012; 2013; Giampietro et al. 2014).

The concept of scale "is only tangentially related to the "size" of a system or a process. Rather it has to do with the established relation between the perception and the representation of a given instance of a type associated with an identity" (Giampietro et al. 2006: 309). In other words, the scale of analysis is the result of the combination of the level of observation (the position of the observer with respect to the observed system, e.g. inside view versus outside view) and of the level of analysis (the coarseness of grain used in the study of the observed system, e.g. microscope versus telescope).

Examples of scales are viability and feasibility assessments. Viability is defined as the compatibility with the internal constraints posed by the structure of a system. For instance, in a country where 70% of the work force is employed by the services sector, 25% by the secondary sector and 5% in agriculture, it is not viable to substitute food imports with domestic production while maintaining the same allocation of labour. This consideration is based on an internal view of the economic process, which takes as its focal point the national scale.

Feasibility is defined as the compatibility with the external constraints posed by the environment. In this case, the feasibility of an increase in agricultural production is given by the availability of land and water resources. This view is based on an external perspective (the limited availability of land, soil, biodiversity and water), which has as it focal point the ecosystem within which the economic process is embedded.

Carrying out a multi-scale analysis consists of considering multiple levels of observation and multiple levels of analysis, for example a component of a system, the whole system and the context of the system. A multi-scale representation makes it possible to describe the *holon* both as a whole and as a part. The use of multiple scales leads to the production of non-equivalent representations of the system. The approach developed in this dissertation is aimed at identifying multiple scales of analysis in the perception and representation of the economy, of water flows and of electricity grids in the three case studies.

The scientific information that is used for governance often consists of producing pictures of the world that serve to advocate a certain cause (Funtowicz and Ravetz 1990). Multi-scale analysis makes it possible to identify these pictures of the world as representations of the observed system. The method consists of providing a multi-scale representation of the systems analysed and mapping the descriptions, claims, recommendations, analytical frameworks and models used for governance according to the multi-scale representation. Multi-scale analysis helps see the system from different points of view and flags how different system definitions depend on the pre-analytical choices of the observer.

An example of multi-scale analysis is given by Giampietro and colleagues (2012) in the comparison of different explanations regarding the death of an individual (Figure 3). All the explanations provided are equally valid, although they refer to different levels of analysis. The choice of scale depends on the context and on the goals of the analyst. Therefore, the use of the explanation "no oxygen supply to the brain" is useful to the doctors operating in an emergency room, but offers no useful information to the ministries deciding on tobacco taxation for example. This multi-scale analysis makes it possible to define which scale is applicable to each problem framing (the pertinence of the analysis) and to define usefulness in relation to the context. Contradictory information results from differences in the choice of scale.

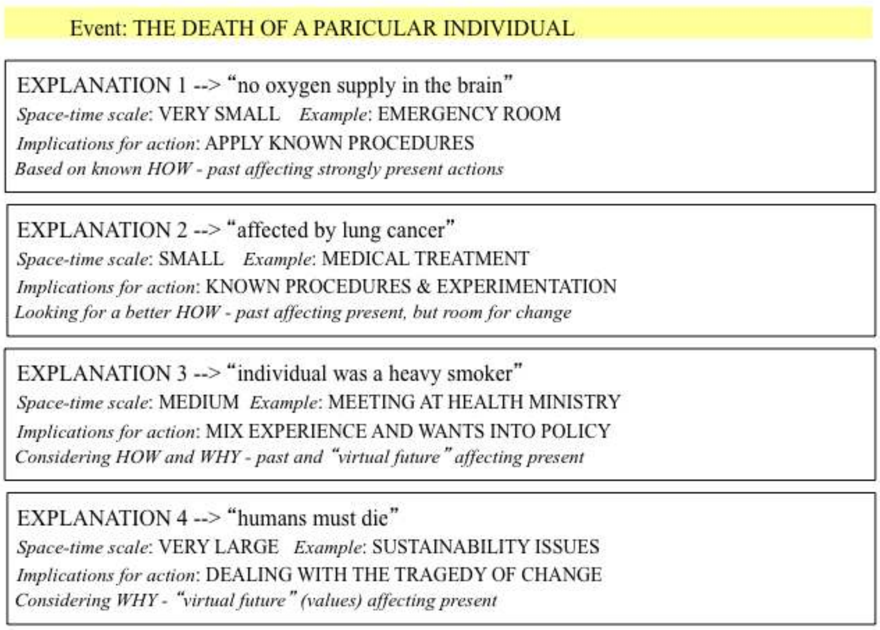

Figure 3. Example of multi-scale analysis. Source: Giampietro et al. 2012: 79.

In his analysis of the concept of social construction, Hacking asserts that “people talk at cross purposes because they have different “whats” in mind. Yet it is precisely the interaction between different “whats” that makes the topic interesting” (1999: 28). Hacking refers to the dispute between the definition of an object as socially constructed and the definition of the concept used to refer to that object as socially constructed. For example, when talking about the child viewer of television, “child viewer” does not refer to a certain type of child but rather to the concept of child viewer created by advertising companies.

In a similar fashion, I use multi-scale analysis to identify what different representations refer to. Simplification can be re-defined as the selection of a specific scale of analysis, which implies focusing on specific properties of the system while necessarily overlooking others. In the case studies presented, I compare the representations and indicators used to a multi-scale representation of the system in order to identify which simplifications have been chosen in each case. The analysis of the level of observation and level of analysis can shed light over the compressions implied by different system definitions and reveal the “whats” of different observers.

The representations under study are evaluated according to their *pertinence* and to their *usefulness*. These two criteria have been chosen in order to provide a quality assessment both according to an external criterion (pertinence) and to an internal criterion (usefulness).

External criteria make it possible to compare different case studies as they provide an external referent. The use of pertinence as external referent concerns the choice of scale of analysis. Different scales of analysis are often related to different levels or sources of uncertainty. Hence, the choice of scale of analysis may have a direct impact on the robustness of the scientific information used, which is a relevant criterion for policy.

However, the use of external referents runs the risk of overlooking pluralism and oversimplifying the assessment of complex issues. For this reason, I also refer to usefulness, which evaluates the quality of each representation according to its own parameters. The use of internal criteria of quality assessment may run into a circular argument. In order to compensate for the drawbacks of each choice, I use both criteria.

Pertinence refers to the consistency between pre-analytical choices and the problem framing. This issue has been flagged by Fjelland (2002) in relation to the research methods used to establish the danger from toxic chemical substances of the waste disposal site of Love Canal. An initial assessment was carried out based on the distance from the disposal site, while only a second assessment revealed that the danger came from water transmission of toxic substances. The failure to consider transmission mechanisms has to do with the uncertainty surrounding the issue of exposure to toxic waste.

This case study is emblematic of the need to ask the right questions rather than providing the right answers to wrong or irrelevant questions (Saltelli et al. 2013). The use of multiple scales of analysis adopted in the case studies highlights inconsistencies in problem framing. For example, in the case of smart grids the focus on consumer behaviour does not relate to the uncertainties involved in the transition towards renewable energies.

The usefulness of the analysis, on the other hand, refers to the consistency between the problem framing and the purpose of the analysis. Since the goals behind specific policy decisions cannot be inferred from a textual analysis or from interviews, the contribution of this approach consists in identifying which scale of analysis is used in the representation of a problem and which policies are consistent with that representation. For example, the analysis of business cycles is not very useful for a policy maker trying to regulate the trade of structured financial products in the stock market.

5.3 Methodological context

This section gives an overview of selected approaches that have been developed for the quality assessment of the science-policy interface from the post-normal science perspective, namely the NUSAP, Knowledge Assessment Methodologies and Sensitivity Auditing. Douguet and colleagues (2009) identify 12 different methods for knowledge quality assessment, including Error Propagation Equations, Expert Elicitation, Extended Peer Review, Inverse Modelling, Monte Carlo Analysis, Multiple Model Simulation, NUSAP, Quality Assessment Methodologies, Scenario Analysis, Sensitivity Auditing, and Stakeholder Involvement.

I have selected those that refer specifically to the epistemological quality assessment of the scientific information used for policy. Methods dealing with stakeholder participation or with specific modelling and data assessment are not described below as they are not directly comparable to the approach developed in this dissertation. I will illustrate the main features and purposes of each approach considered in order to highlight the contribution of the use of multi-scale analysis.

The first method for the assessment of quantitative information is the NUSAP system developed by Funtowicz and Ravetz (1990), and later by van der Sluijs and colleagues (2005). The NUSAP system consists of a quantitative and qualitative assessment of the uncertainty present in quantitative information. The indicators or models analysed are classified in terms of *Numeral* (the quantity), *Unit*, *Spread* (statistical error) on the quantitative side, and *Assessment* (the quality of the information) and *Pedigree* (the quality of the process producing the information) on the qualitative side.

The NUSAP system has been widely applied to a variety of case studies, such as the uncertainties surrounding climate change predictions (Wardekker et al. 2008), groundwater modelling (Refsgaard et al. 2006), and the monitoring of emissions and environmental assessment in the Netherlands (van der Sluijs et a. 2005). The Netherlands Environmental Assessment Agency has adopted NUSAP as part of its Guidance on Uncertainty Assessment and Communication (Saltelli and Funtowicz 2013).

The NUSAP system highlights the uncertainties associated with the production of quantitative representations, both at the level of measurement and at the level of the model uncertainties. The various categories make it possible to assess the quality of the estimates used and the possible trade-offs between, for example, reliability and significance (Funtowicz and Ravetz 1990). The Pedigree category gives an additional sense of the confidence of the experts involved about the data and measurement schemes adopted (van der Sluijs et a. 2005). The contribution of this method of quality assessment is that it makes the vagueness and ambiguity associated with the inputs and measurement methods explicit and easy to communicate to policy makers.

Developing further the concept of Pedigree put forward by the NUSAP scheme, the Knowledge Assessment Methodologies were developed as a way to assess the quality of the scientific knowledge and of the process of policy-making based on such knowledge (Guimarães Pereira et al. 2007; Corral Quintana 2009). The assessment is based on four main areas, which may be defined in different ways depending on the application:

(i) The framing of the problem and the definition of fitness for purpose;

(ii) The assessment of the sources of uncertainty, for example the consideration of the sources of information, both in terms of methods and of actors;

(iii) The testing of the performance of the model, for example the applicability and the reliability of the information used as input for the generation of knowledge; and

(iv) The review of the model itself, for example by looking at the legitimacy and consensus surrounding the scientific information used (Douguet et al. 2009).

This framework focuses on three main components of policy-making, namely the information used, the decision-aid tools used and the role of the analyst (Corral Quintana 2009).

Knowledge Assessment provides a systematic approach to the assessment of the knowledge inputs used for governance. The concept of Pedigree is here extended to the assessment of qualitative information. Corral Quintana (2009) defines three main attributes to be used for Quality Assessment, which are associated with their relative criteria (in brackets). The attributes are applicability (accessibility, availability and intelligibility of the sources of information), fitness for purpose (adequacy, relevance, accuracy and completeness of the information), and reliability (method generation, verification, extended peer acceptance and colleague consensus).

It should be noted that the concept of fitness for purpose is defined in this framework in a different way than that used in this dissertation. In Knowledge Assessment Methodologies, fitness for purpose answers the question "does the model fit the problem or is the problem being adapted to fit the model?" (Corral Quintana 2009: 60).

In order to assess the role of the analyst, two additional attributes can be considered, namely competence (experience, adaptability and methodological choices) and legitimacy (control and acceptance) (Corral Quintana 2009). These categories make it possible to highlight for example the absence of references and self-referencing, omissions and specific focuses (Guimarães Pereira et al. 2013).

A third approach is that of sensitivity auditing proposed by Saltelli and colleagues (2013). Sensitivity auditing calls for transparency in the understanding of "the different sources of uncertainty and their relative importance" (Saltelli and Funtowicz 2013: 81). The approach consists of a set of seven rules designed to check the pertinence of the formal models used (check against the rhetoric use of mathematical modelling), the quality of the assumptions (adopt an assumption hunting attitude), the quality of the input (detect "garbage-in-garbage-out"), the robustness (find sensitive assumptions before they find you) and transparency (aim for transparency) of the models, the relevance of the research question (do the right sums and not the sums right), and the application of sensitivity auditing itself (focus the analysis). The last rule is of particular interest, as it introduces the element of reflexivity. Sensitivity auditing is not meant to be a "perfunctory" exercise (Saltelli et al. 2013) but rather an assessment of whether the issue under study should be studied at all.

Sensitivity auditing moves slightly away from the goal of providing policy-makers with a quality assessment of the information, quantitative and qualitative, used for governance and is rather a guide to be used by the analyst(s) producing scientific information. In this sense, sensitivity auditing focuses not only on the inputs and methods, but also on the process of production of scientific information, including the formulation of the research question, the handling of the assumptions and uncertainties involved in modelling and the self-evaluation of one's analysis. Sensitivity auditing serves as a tool both for the assessment of fitness for purpose and for the assessment of that purpose. On the other hand, this broader focus is presented in the form of guidelines and is less structured than the other approaches, making it not so readily applicable.

The contribution of the multi-scale analysis developed in this dissertation consists of focusing on a different aspect of quality assurance, namely on the source of controversies or contradictions between different representations of the same system. Instead of analysing the quality of the inputs, framing or application of scientific models to specific sustainability issues like the other approaches in this field, multi-scale analysis puts emphasis on the relationship between pre-analytical choices (including normative choices) and the resulting representation of the problem. Hence the idea of checking the relevance of the research question formulated about sustainability issues is further developed by multi-scale analysis.

The assessment of the pertinence of the representation is closely related to the idea of correspondence used in Knowledge Assessment and the quantitative Pedigree. The focus on the usefulness of the representation recalls the practical recommendations put forward by Sensitivity Auditing. Like the latter approach, multi-scale analysis offers a series of guidelines, rather than specific steps to the performance of quality assessment, and offers some insights that can enable the assessment of the purpose.

The different approaches presented in this section also have different targets. NUSAP is most appropriate for the analysis of the uncertainty related to quantitative information. Knowledge Assessment Methodologies can be applied both to quantitative and qualitative information, but have a specific focus on the sources of uncertainty. Sensitivity Auditing is directed to the assessment of the procedure used to produce scientific information for governance. Multi-scale analysis contributes to widen the scope of application of quality assessment by focusing on the uncertainty related to the plurality of quantitative representations used for governance, and is thus most appropriate for the study of controversies and cross-cutting sustainability issues.

The approach developed is not meant to give answers or solutions to the sustainability issues analysed, but rather to identify how different perceptions lead to different choices of scale that result in contradictory representations of the same system. Similarly to the Pedigree analysis and to Sensitivity Auditing, multi-scale analysis can help promote a reflexive debate on pre-analytical choices and a on the normative aspects of the representations used.

5.4 Limitations of the approach

The multi-scale analysis applied in this dissertation is based on the idea of multi-purpose grammar used by the MuSIASEM approach (Giampietro et al. 2009). That is, the system under study is formalised in a different way in each case study based on the use of a set of semantically open categories. The concept of grammar refers to an analysis based on the expected relations between semantic categories (referring to the functions, the why) and formal categories (referring to the structural components, the what/how) (Giampietro et al. 2009). In other words, the description focuses on the functions, which can be formalised in a variety of different ways. For example, the function of *greeting* (the why of a written element) in a letter can be formalised as “Dear Sir/Madam” or as “Hey” (the what/how of the written element). Semantically open means that the *meaning* is open and has to be defined according to the specific function of the object under study in each situation. For example, the financial sector is considered as a driver of the economic process in the first case study based on the adoption of an economic narrative and as part of the services sector accounting for resource consumption in the other two cases, based on the adoption of a biophysical narrative. In addition, the description of the financial sector can be formalised by distinguishing between financial institutions, insurance companies, private and public institutions, and so on, or simply as an economic sector.

The strength of using semantically open categories is the flexibility and adaptability of the method. For this reason, multi-scale analysis can be applied to such different case studies as the economic theories behind the financial crisis and the technical assessments of water management. On the other hand, the weakness of the approach is that there is no standard procedure for applying it. The consideration of multiple scales of analysis as an analytical tool requires some knowledge of the system under study and of the functions performed by its components. Put in a different way, the application of a multi-scale analysis requires craft skills. The Pedigree assessment of NUSAP is based on the same requirement (Funtowicz and Ravetz 1990). As Beck and colleagues (1994) put it, experience and doubt are the starting points to handle uncertainty. The trade-off implied by this type of assessment methods is that the analysis is hard to reproduce. This down side can be seen as the price to pay for using a complexity perspective. As Porter (1995) argues, simplification is key to standardisation, which allows for the reproducibility of research methods.

A second weakness is that complex representations of a system are not very practical in guiding policy making or participatory processes. The multi-scale representations offered in the case studies serve to highlight the constraints, feedback loops and bottlenecks of the system rather than to offer a solution. Hence, the criticism of the representations used for governance does not come with a better alternative. To some extent, the proposal of an alternative is out of the scope of this dissertation. What I offer are some tools to contribute to the quality assurance of the scientific information used for governance and to the understanding of complexity and uncertainty, not the scientific information itself. Nevertheless, other approaches have been developed with the aim of both highlighting the complexity of sustainability issues and offer practical tools for decision making.

Examples of such methods are the ethical matrix developed by Mepham and colleagues (2006), which focuses on the ethical implications of emerging technologies, and social multi-criteria evaluation developed by Munda (2008), which is a decision support tool aimed at managing incommensurable perspectives.

Both methods make use of matrices in order to map the different values and descriptions of a system, in a similar fashion to what is proposed by the multi-scale representation. However, matrices are faced with the issue of weighting and aggregation of non-equivalent and non-reducible indicators (Saltelli 2007). Therefore, these decision-making support tools have to be used with extreme care and may also serve primarily the function of highlighting the sources of controversy (De Marchi et al. 2000).

Finally, the approach developed cannot be applied to the study of any issue. The focus on the plurality of representations used in the description of complex issues makes this approach very useful for the study of sustainability issues, by highlighting the differences between the observation of economic agents and of the system as a whole, between the internal view of water and energy use and the external view of availability of favourable gradients from the environment. However, the multi-scale representation has limited explanatory power when it comes to the assessment of controversies over privacy and data protection issues, over human rights, or over healthcare. For this reason, the multi-scale approach developed in this dissertation should be seen as complementary to other research methods.

6. Case studies

6.1 Description of the case studies

Three case studies are presented in this dissertation, with varying levels of uncertainty and complexity. The presence of uncertainty implies that the "task of getting the facts right" is not always fully feasible (van der Sluijs 2012: 174) and opens the way for the production of a plurality of non-equivalent representations. The case studies show how these representations reflect not only differences in descriptive choices but also differences in normative choices, resulting in more or less visible controversies and contradictions.

Multi-scale analysis is applied to the representation of the system under study and used to allocate the plurality of competing narratives and descriptions of the problem to different scales of analysis. The three case studies illustrate the use of quantitative scientific information in three different policy arenas: the governance of the economy, the management of natural resources and emerging technologies. The diversity of these three different cases offers the opportunity to discuss the contradictions that emerge from very different perspectives on the uncertainty and complexity associated with the system under study, and thus to move beyond the specificities of each case.

The case studies illustrate a variety of different representations of the issues under consideration and highlight the complementarities and inconsistencies between these representations. The consideration of multiple perspectives makes it possible to assess both differences in the choice of scale of analysis and in the choice of problem definition. As a consequence, the analysis of the representations used in each case study provides examples of the interaction between the normative and descriptive aspects.

The case studies are presented in the order in which they were written during my PhD, although the content has been partially revised. The treatment of the case studies evolved along with my understanding of the challenges of the science-policy interface. In the first case study, I start with a criticism of neo-classical economics and its use for governance. In the second case, I turn to integrated assessment as a way to include more perspectives in the same analysis. Finally I include interviews and the analysis of normative aspects, as I understood through practice that better science is not enough. I thus experienced through my research that the science-policy issue is not just a problem of doing the sums right, but also of doing the right sums and of engaging with the questions of “what makes the sums right?” and “who decides what is the right sum?”.

I will give an overview of (1) the sources of uncertainty in the issues considered; (2) the contribution of the multi-scale perspective to the problem framing in each case; (3) the plurality of perspectives and the controversies surrounding each case; and (4) the relevance of the case studies to the field of sustainability science used for governance.

6.2 The legitimacy crisis of the economic paradigm

The first case study is an analysis of the 2007-08 financial crisis and of the economic models used to describe the behaviour of economic agents and of the economy as a whole. Uncertainty in this case study is associated not only with the risk of sub-prime mortgages and structured financial products, but also with the problem definition since the socio-economic system is a complex system composed of many different subsystems that interact in a non-linear way and that evolve in time. The presence of multiple sources of uncertainty poses a challenge both in technical terms with respect to the calculation of risk of financial products and in epistemological terms with respect to the representation of the dynamics of this complex system.

An alternative description of the events leading to the financial crisis is offered based on the theoretical concepts provided by hierarchy theory, namely the concept of *holon* and of multiple scales. Economics as a discipline is divided between microeconomics and macroeconomics, which I associate with two different scales of analysis. The definition of scales in this case study is therefore quite straightforward. The contribution of the case study consists in highlighting the inadequacy of using the same analytical tools at different scales of analysis. The multi-scale perspective highlights the different roles assumed by financial institutions as rational economic agents and as regulating the flow of money, broadly defined to include financial assets, in the economy.

This case study is particularly interesting because the contradictions that emerge between different representations are not due to the use of different disciplines, but from different choices of scale within the same discipline. This consideration makes it clear how differences in the choice of scale of analysis lead to very different representations of the system and definitions of causality relations between the observed phenomena. For example, from the microeconomic perspective profit maximisation leads to rational decision making, whereas from the macroeconomic perspective profit maximisation resulted in rent-seeking and loss of information. As a consequence, the choice of scale of analysis has much deeper implications than just offering different perspectives, as it may result in inconsistent representations of the system.

The interest of the financial crisis of 2007-08 from the point of view of sustainability science is two-fold. The economic crisis that ensued led to a drastic reduction of wealth, public spending on welfare and to an increase in inequality. As a consequence, the economic sustainability of the countries hit by the crisis is questioned. On the other hand, acknowledging the impossibility of perpetual economic growth in a finite planet, leads to an analysis of the mechanisms through which economic growth is achieved and maintained. According to this interpretation, the financial crisis can may indicate that the productive economy is affected by biophysical constraints posed by the environment.

6.3 Assessing sustainability: The societal metabolism of water in Israel

The second case study deals with water management in Israel. This case also presents different levels of uncertainty, since there are uncertainties associated with the modelling of groundwater tables, of aquifer location and recharge, with measurements of salinity and with predictions about future water demand and population growth. In addition, different dimensions of uncertainty have to be taken into account, including the epistemic dimension related to the representation of the issue and the social dimension related to conflicting interests.

A variety of different, and at times contradicting, narratives about water are identified, ranging from more technical formulations of the problem as a matter of water scarcity or efficiency in water use to more political formulations focusing on inequalities over access to, and distribution of, water. The case study focuses on the State of Israel, as defined by the Israeli government, and its citizens. It should be noted that both the definition of the geographical boundaries of the State and of the Israeli population are controversial topics, but those debates are out of the scope of my case study. Therefore, equity issues in the case study are considered in relation to different social groups within the Israeli society, and not in relation to Israelis and Palestinians.

The multi-scale representation of the system makes it possible to allocate the different claims about water and water-related problems to different scales of analysis and reveals how the choice of scale in the representations used by the government overlooks distributional issues in favour of a more technocratic approach to water management. At the same time, technical descriptions of water consumption are also at odds with each other, adding to the general lack of clarity that characterises Israeli narratives about water. The multi-scale analysis shows how different disciplinary approaches are opposed to each other or integrated relating to the different definitions of strong and weak sustainability.

This case study is an obvious example of contradictory knowledge claims and offers a great example of the contribution of multi-scale analysis in identifying the contradictions in the representations and indicators used to describe water issues. The political conflict is reflected in the use of contradictory or inconsistent representations. This case study clearly highlights the relationship between the descriptive and the normative aspects of the representations under analysis.

Normative choices are reflected both in the framing of the debate and in the silences over issues not belonging to the chosen frame.
The case study is relevant to sustainability science for policy not only in its more obvious aspect of managing scarce resources, but also in relation to the type of scientific information that is given priority in the policy context. The focus on technical aspects drives the debate towards a very specific approach to water management and gives a prominent role to expert knowledge. This problem framing depoliticises water management, by overlooking the social, political and historical context in favour of a more positivist representation of the problem. This situation is not peculiar to the Israeli context, as similar narratives and problem framings can be found in a variety of case studies, for example, in the case of Cyprus (Alcantara Escolano et al. 2012), Spain (Madrid and Kovacic 2014), Greece and Portugal (Kallis et al. 2006). In this broader context, the multi-scale approach can serve in promoting reflexivity about the usefulness of framing the debate on water management in technical terms.

6.4 Empty promises or promising futures? The case of smart grids.

The third case study addresses the challenge of evaluating and designing policies for emerging technologies, focusing on the case of smart grids. Emerging technologies are characterised by high levels of uncertainty. In this case, there are uncertainties associated with the potential benefits of smart grids, with the possible risks, with unforeseen effects, with the impact that the new technology may have on the structure and dynamics of the system to which it is applied, and so on.
The object of study in this case is not a material object but the set of promises surrounding this emerging technology. Smart grids are presented through a myriad of, at time contradictory, promises about the future in relation to increased efficiency, security of supply, the transition towards renewable energies and the consequences of such a transition for the economy and for society. At the same

time, the use of smart meters associated with the automation of electricity grids comes with potential threats to privacy and data protection.

A multi-scale representation of electricity grids is provided in order to evaluate the pertinence of the representations of smart grids used by practitioners in the field, the usefulness of these representations in relation to the declared goals, and the relevance to the wider social context. The multi-scale analysis reveals how different levels of analysis are used interchangeably when referring to the potential benefits and to the scope of application of the emerging technology. Social and ethical aspects are confined to the discussion of privacy issues and overlooked in relation to long-term societal impacts of an energy transition.

A reflexive analysis of the goals and ideals associated with smart grids was carried out in a workshop with practitioners in the field in which I took part. More specifically, the participants of the workshop were asked to reflect upon the social robustness of the technology under study and on the role of the lay public in the decisions regarding the development and deployment of smart grids. This is the only case study in which there was an explicit discussion of the normative choices and value judgements of the experts involved.

The interest of this case study relies precisely on the ability of the multi-scale analysis to shed light over how smart grids respond to the existing controversies related to privacy and data protection and to renewable energies, sustainable development, and the idea of the green economy. The analysis shows that, similarly to the previous cases, a technocratic approach is favoured both in the description of the issues and in the consideration of the social robustness of the technology.

Emerging technologies are a typical case study used to illustrate how scientific information is used for governance (see for example Delgado et al. 2013). The choice of case study was thus motivated by the opportunity to show how the multi-scale approach developed in this dissertation can contribute to the assessment of the objects of techno-science as well as serve as a debate support tool in the consideration of social and political values involved in policy making for growth and innovation.

Chapter 2

Case study: The legitimacy crisis of the economic paradigm.[2]

1. Introduction

In this case study, the global financial crisis of 2007-08 is analysed through the insights provided by hierarchy theory. The changing role of financial intermediaries is analysed both at the micro level with respect to the profit maximisation rationale of banks and at the macro level in reference to the role of the financial sector in regulating monetary flows. The central tenet is that the individual and the social scales cannot be analysed using the same theoretical approach. For this reason, the pertinence and usefulness of the representations and models of the economy produced by neo-classical economics is questioned.

The sluggish response to the financial crisis can be understood in terms of a progressive loss of information, increased uncertainty and the rise of technocratic approaches to financial economics. The loss of information is a consequence of normalisation, defined for the purposes of this case study as the reduction of measurements on different descriptive domains to one common descriptive domain. Normalisation is a form of simplification.

Normalisation leads to a reduction in the diversity of perceptions and representations of the external world. Signals coming from the external world are forced into a uniform standard of variables with a consequent loss of relevant information. The systemic loss of relevant information increases uncertainty. In the case study analysed, normalisation consisted of the pooling together of information on high- and low-risk borrowers first, assets and debts second, private and public debt last. The mixture of signals deprived the market and its agents of the means to

[2] This chapter has been adapted from Kovacic (2013).

deal with the crisis. This chapter reinterprets the events that led to the financial crisis by opposing the systemic view of multi-scale analysis to the reductionism of normalisation.

In this case study, the consequences of simplification for the science-policy interface are analysed in depth. I argue that the simplification of information contributed both to causing the financial crisis and to the inability of governments to recover from it. Simplification has to do not only with the scientific information produced and used by financial intermediaries in financial markets, but also with the policies designed to cope with the crisis, which applied a single strategy (e.g. austerity) to very diverse contexts. The process of simplification led to a drastic reduction of pluralism and created a serious inability to understand complexity and to cope with uncertainty.

The financial crisis of 2007-08 is a matter of sustainability science for two reasons. Firstly, the financial crash and the economic crisis that followed have compromised the economic sustainability of many Western economies in terms of reduced welfare, increasing inequality and a worsening of prospects for the future generations.

Secondly, the financial crisis can be linked to peak oil. Peak oil refers to the prediction that the maximum production capacity of oil will soon be reached, limiting the pace of oil supply in a context of increasing demand (Campbell 2004; Murray and King 2012). According to Hall and Klitgaard (2012) peak production was reached already in 2004. Once the maximum production capacity of oil has been reached, oil supply becomes inelastic. This situation can be described as absolute scarcity.

According to neoclassical economic theory, in the case of moderate scarcity, prices adjust so as to bring demand and supply to equilibrium. In the case of absolute scarcity, the biophysical limits to economic growth based on productive activities become more evident. As a consequence, economic growth has shifted more and more to the financial sector (Hall and Klitgaard 2012; Gamble 2014). However, economic growth based on financial speculation presents a number of problems, such as increased fragility to financial crises (Taleb 2007), a shift of capital accumulation away from the real economy (wages) towards the financial economy (financial capital) (Gallino 2011), increasing inequality (Pikkety 2014), and so on.

The chapter is structured as follows. Section 2 gives an overview of the events that led to the financial crisis, starting from the subprime mortgage crisis in the US, and leading to the global financial crisis and to the sovereign debt crisis of peripheral European economies. I highlight the normalisations that occurred leading to a simplification of the representations used to guide decision making both at the individual level and at the level of institutions. The third section introduces the different descriptive domains used in economics, namely, microeconomics and macroeconomics. The systemic view adopted highlights the limits of the tools used by conventional economics in explaining the crisis. The fourth section shows how the technocratic narrative hides the uncertainties inherent in the economic system through the use of allegedly neutral mathematical and statistical models. In such a context, only the experts can deal with the crisis thanks to their specific knowledge, assumed to be valid by default.

I argue that the financial crisis is a legitimacy crisis of technocratic knowledge. More and more in modern states, democratic knowledge requires a political system that can deal with epistemological relativism, that is, define what is relevant according to the diversity of perceptions present in society. The concluding remarks note that experts do not have the means or the legitimacy to guide decision making given the high uncertainty that characterises the financial system. The use of mono-scale indicators such as risk ratings deprives policy makers and experts alike of the information and tools needed to deal with the crisis.

2. What happened?

This section explains the financial crisis as a series of successive normalisations, which led to a strong hegemonisation in the choice of narratives used to represent the economic system and to a progressive loss of the ability of gathering useful information and developing tools to control and monitor the financial market. Normalisation is a way of dealing with complexity, by reducing all relevant information to a manageable set of variables. In this simplified representation, the observed phenomena are characterised according to a single defining category of observable attributes that is used to study a trend and then to predict by inference the behaviour, or probability of occurrence, of future phenomena.

The progressive loss of information leading up to and aggravating the financial crisis is divided into three steps or normalisation mechanisms, namely, the blurring of prime and subprime mortgages, the securitisation mechanism and the substitution of private by public debt. I give an overview of the events leading up to the crisis and of the unfolding of the latter, as well as of the simplified models and representations of financial mechanisms that resulted in a poor governance of uncertainty and complexity.

What is now known as the global financial crisis started as a mortgage crisis in the US in 2007 that expanded to financial markets and took on a global dimension. The mortgage crisis started with the excessive issuing of subprime mortgages associated with the housing market. Subprime mortgages are loans that present a high risk of default because of the limited capacity of the borrower to repay the debt. The creation of subprime mortgages originally responded to the US government's initiative to provide home ownership to a larger share of the population. The Federal National Mortgage Association, known as Fannie Mae, and the Federal Home Loan Mortgage Corporation, known as Freddie Mac, were created after the Great Depression for the very purpose of facilitating access to house mortgages to lower income families (Fannie Mae 2013). The financial crisis can hardly be attributed to this type of social policy, nor traced back to the 1940s. The proliferation of subprime mortgages is better explained as the result of the profit maximisation logic pursued by banks as rational economic agents at the individual scale, which is incompatible with the welfare rationale pursued by the government at the societal scale.

In order to minimise risk, banks (used to) screen all potential borrowers and select candidates according to their capacity to pay back the loan. This practice limited the number of potential clients who could access financial services. The problem was solved through the issuing of subprime mortgages, that is, mortgages subject to refinancing every two or three years. Refinancing refers to the redefinition of the interest rate paid on the loan based on house prices and on financial market borrowing costs, measured by indexes such as the London Inter-Bank Offered Rate (LIBOR). Inter-bank borrowing costs can be seen as a measure of the confidence that different financial institutions have in each other's capacity to service debt.

Following the refinancing mechanism, if the value of the purchased assets increases in the house market (due to speculation) or in the financial market (due to better conditions offered on loans), the interest paid on the mortgage is renegotiated so as to match the new conditions of the market. The ability of the borrower to repay is linked to the price of the asset, and as house prices were rising in the US, the value of the asset purchased would rise and so should the borrower's capacity to repay the loan (Gorton 2008). Since the borrower shares the gains from the housing market's appreciation, they have a greater incentive to keep paying the loan. However, the assets created are directly exposed to fluctuations in house prices. As happened in the US, if the economic venture stops growing trouble sets in: once the prices of houses flattened, subprime mortgages could not be repaid.

The proliferation of subprime loans can be understood in terms of normalisation, that is, a reduction of all relevant information to one single indicator. Borrowers are reduced to statistical characteristics, where "all important information can be reduced to a set of numbers and converted to quantifiable default risk" (Marglin 2011: 15). Credit insurance policies, which offered the illusion of zero risk trade, also played a role in the normalisation process, as discussed below. Following this mechanism, the only relevant variable is the capacity to repay the loan, and a variety of economic agents are classified into just two categories: prime or subprime borrowers. Since the market can now rely on default risk indicators, the identity of the borrower becomes irrelevant.[3] The number of potential borrowers

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3 As opposed to microcredit, where credit is given based on the identity of the borrower, their community ties, neighbours' references, and so on.

increases at the cost of a loss of information, and of a reduction in the effectiveness of risk control mechanisms.

Subprime mortgages were financed through securitisation, that is, the creation of financial derivatives from a pool of mortgages, prime and subprime. Banks created financial derivatives called securities to be sold to investors as a means to raise capital which in turn could be lent to borrowers. The high risk associated with subprime mortgages is thus distributed to a variety of securities and reduced to a small percentage of the new financial derivative. A laxer screening of borrowers is required, because high risk mortgages can be redistributed to a number of securities. The Mortgage Backed Security (MBS) created is itself subject to fluctuations in house prices. Securitisation opens new channels of transmission of risk from one market (housing) to another (financial). MBSs can be seen as risk-transferring devices (Carbó-Valverde et al. 2012), enhancing the asymmetries of information associated with risky assets.

Securitisation offered a great incentive to take on new risk, as this could be redistributed to different financial products. Mortgage backed securities were themselves used as collateral, that is, as protection against a borrower's default, to create Collateralised Debt Obligations (CDO), a type of security backed by a variety of assets associated with different risk levels, structured in tranches so that investors are repaid in a prescribed sequence. In other words, MBSs were pooled together with other securities, split into different chunks and used to create a new type of security: the CDO. CDOs create additional risk, as they add new transactions to the existing mortgages. "There are (at least) two layers of structured products in CDO. Information is lost because of the difficulty of penetrating to the core assets" (Gorton 2008: 62). CDO issuance tripled over the period 2005-07 (Gorton 2008). CDOs were further developed into a cash flow CDO – where the mortgage is actually bought and used as debt collateral – and a synthetic CDO – where the obligation is guaranteed through a Credit Default Swap (CDS), that is, an agreement that guarantees that the seller buys back the asset in case of default.

CDSs can be seen as a type of insurance against default on underlying risk, when this risk can no longer be measured. Since CDOs contain different securities linked to different risk levels, instead of trying to calculate the risk associated with the new financial derivatives, CDSs were created as insurance against risk. CDSs transfer the risk of default form the buyer to the seller of the financial derivative in exchange for the payment of a premium (Terzi and Uluçay 2011).

In the context of diminishing information due to the restructuring of financial products into new exotic products, this type of insurance became the most traded derivative. CDSs came to be traded as financial products themselves. The CDS market experienced a spectacular growth from $1 trillion in 2001 to $54.6 trillion in 2008 (Terzi and Uluçay 2011). The nature of CDSs also broadens the scope of actors involved in transactions, and insurance companies come into play as well as credit-rating agencies, which determine the price of CDSs. The involvement of a plurality of agents aggravates the potential for the asymmetrical bearing of risk among the different actors involved, a point to which I will return to later.

I characterise the creation of new financial products as a second type of normalisation. Securitisation allows for the inflation of assets through leveraging (where asset value is amplified by the increased number of transactions), independently of whether the value created is real or virtual. Loan pooling leads to a destruction of information (Carbó-Valverde et al. 2012). Normalisation is taken to a second step, reducing all sorts of assets and debts to pooled financial derivatives and making it impossible to distinguish real from virtual capital. After this step is taken, the composition of the financial derivatives traded becomes completely irrelevant. Additionally, the creation of CDSs reduces risk itself to a tradable product.

The loss of information creates the need for rating agencies to evaluate the risk associated with the various financial products traded. The main credit-rating agencies are Standard & Poor, Moody's, and Fitch Ratings, which offer ratings on the credit quality of securities traded in markets worldwide. Ratings are based on the estimated solvency (capacity to pay back the loan) of the issuer, and are calculated based on information provided by the issuers themselves on their operations, finances, and management plans. Ratings also serve to determine the interest rate that companies pay on their debt and the price at which debt is traded (Business Week 2002).

Rating agencies aggregate information on the behaviour of financial institutions, so that ratings act in financial markets in similar fashion to price in commodity markets. In a perfect competition economic model, prices ensure equilibrium between demand and supply through the market mechanism. However, the rating mechanism is not as neutral as (supposedly) the perfect competition price mechanism insofar as the main shareholders of rating agencies are the issuers themselves, including investment banks, hedge funds, and insurance companies.

The London Inter-Bank Offered Rate (LIBOR) presents an interesting example of the conflict of interest that banks may face when providing information on their estimated incurred risk. Financial indicators such as the LIBOR are used to calculate both returns on personal mortgages and on investment and pension funds. LIBOR measures banks' borrowing costs and is calculated on a daily basis, based on estimates provided by the largest 16 banks. All submissions are published, top and bottom ratings are excluded, and the index is calculated as the average of the remaining rates.

In times of crisis "all banks might be tempted to submit artificially low LIBOR estimates" (The Economist 14/04/2012). Barclays is under investigation over a scandal on rate fiddling during the peak of the 2008 crisis, where it figures as the highest average submitter. Given that financial market stability is closely linked to ratings, it is unsurprising that the former chief executive of Barclays declared that rate manipulations followed a suggestion by the Bank of England that Barclays did not always need to appear as high as they had on LIBOR (The Economist 07/07/2012). In other words, the rating mechanism enhances the loss of transparency and the blurring of the line between the private and the public spheres.

The reduction of information implied by the use of normalised indicators such as risk and of the increased reliance on intentions-conveying ratings, opened the way to moral hazard at the individual scale, ultimately leading to a market failure at the macro scale. Moral hazard is a "situation in which one person makes a decision about how much risk to take, while someone else bears the cost if things go badly" (Krugman 2009). Moral hazard in this context occurs when there is asymmetric information on the amount or location of risk. In the case of the 2008 financial crisis, these variables were unknown to all the players so that moral hazard became a systemic problem.

The creation of collateralised securities led to the practice known as "shadow banking" whereby credit is given with the purpose of distributing it rather than holding it until maturity (Andersen et al. 2011). The restructuring of loans into new securities allows banks to create new capital more rapidly, that is, before the original loans are serviced by borrowers. This in turn allows for higher leverage, that is, a higher ratio of credit to capital. The function of banks thus went from that of regulating the flow of credit to that of creating new credit (or debt). This practice is also known as originate-to-distribute (Gorton 2008), as the credit created leads to more trading, instead of being held by the issuer. New risk is diluted to a variety of products, reducing the risk of single investments but increasing the overall risk of the financial market.

A similar interpretation is offered by the principal-agent argument. The principal-agent problem describes a "potential conflict of interest between 'principals' whose resources are being deployed to some economic end and 'agents' who act on behalf of principals to carry out the deployment" (Marglin 2011: 14). The conflict of interest arises when the agent benefits from the number of transactions carried out and not from the outcome of those transactions. However, in the long run, financial intermediaries need to guarantee returns to their investors if they are to keep their clients, so that their interests should converge.

At the micro level, financial agents responded rationally to the new opportunities that arose, by exponentially increasing the number of clients and financial products marketed. At the macro level, the loss of information deprived agents of the instruments needed to recombine diverging interests in the long term. Therefore, the principal-agent problem, or the systemic moral hazard created, are better explained as a change in descriptive domain at different time scales. According to Kalecki (1991), the economy operates in historical time, where investment decisions and actual investments do not occur simultaneously, causing imbalances in the economy. The complexity of the financial system (Minsky 1992) lies in its changing function at different scales of analysis at different points in time.

The trigger of the financial crisis can be traced to the collapse of Lehman Brothers. Due to the proliferation of structured financial products, the market was "awash with capital but short on liquidity" (Lapavitsas 2009: 121). In other words, financial institutions had built financial assets without having the money to repay obligations. Once the housing bubble burst, subprime loans could not be refinanced, a large amount of borrowers started systematically defaulting on their mortgages, and banks did not have the capital necessary to pay their debts. The lack of liquidity led to insolvency. Bear Sterns was the first bank to fail, and was bailed out by the US government. Fannie Mae and Freddie Mac followed suit and needed government support. With Lehman Brothers the situation changed, as the government did not rescue the bank.

After failing to sell its assets, Lehman Brothers declared bankruptcy in September 2008. Lehman Brothers had re-hypothecated many of its clients' assets to the point where it could no longer measure the level of risk associated with its financial products. In fact, after bankruptcy, many of these assets could not be returned (Aragon and Strahan 2011), and insolvency turned into liquidity loss. The bank had to service its debts with the little capital it actually owned, which in turn diminished liquidity even further.

The collapse of Lehman Brothers turned the mortgage crisis in the US into a financial crisis that went global, as it affected the equity indexes of financial markets all over the world (Bartram and Bodnar 2009). Thanks to the high ratings the bank received from rating agencies, Lehman was a big swap counterparty in the interbank market, that is, a key player connected to many international institutions. In particular, Lehman had a liquid CDSs (risk insurance derivative) with low probability of default that was selling cheap on the market. The default of

Lehman triggered those payments guaranteed by CDSs, leading to huge losses across the financial sector on a global scale.

The effect was seen with the bankruptcy of the insurance company AIG almost immediately after Lehman. Insurance companies cover events that are assumed to have independent probabilities and are not prepared for generalised losses, such as those caused by natural catastrophes. In this sense, Lehman was like a natural disaster causing generalised default on all purchasers of its CDSs and triggering losses over the whole financial market.

Kindleberger and Aliber (2005) explain financial crises as cycles of manias, defined as the exponential increase in the supply of credit in the form of real estate, stock or currency bubbles, followed by panics, due to the bursting of the bubble. “During economic expansions investors become increasingly optimistic and more eager to pursue profit opportunities that will pay off in the distant future while lenders become less risk-adverse” (Kindleberger and Aliber 2005: 12).

Minksy (1992) distinguishes between hedge finance (when income flows are able to meet the financial obligations both of the principal (actual loan) and interest payments), speculative finance (when income flows are able to cover only interest payments and thus new debt has to be issued in order to meet payment commitments), and Ponzi finance (when income flows are not sufficient to fulfil either the principal or the interest payments). Financial crises are caused by a shift towards speculative and Ponzi finance, which results in increased risk.

The proliferation of subprime mortgages first, and exotic financial derivatives and insurance premia successively, constituted the asset bubble. The inclusion of new borrowers led to the introduction of new levels of risk in the financial market, which was not matched by the introduction of a new regulatory framework to deal with the extra risk. The new financial products greatly contributed to the instability of financial markets, as risk was spread and redistributed to new players, new products and new markets. The increased instability can be attributed to the moral hazard implied by the new unregulated opportunities for investment and speculation.

Due to the high level of integration of financial markets and the chain reaction caused by claims on CDSs, it is argued that the crisis took off as a global financial crisis from the beginning (Kamin and Pounder DeMarco 2012). The devaluation of equities implied that more and more selling orders were filed, further lowering quotes for equities in a downward spiral. Once securities started losing value, purchasers rushed to sell them back to the financial market in order to minimise losses. The increase in sales further lowered the value of the assets traded. The result was a destruction of equity value of $29 trillion between September 2008 and February 2009, equivalent to 50% of global GDP (Bartram and Bodnar 2009).

Given that financial products are used mostly to finance other financial products, that is, the virtual value generated stays in the financial circuit and does not directly enter the real economy, this loss was not felt with the same magnitude in terms of GDP. Nonetheless, the loss of value did not only concern financial markets but also affected other industries, since financial assets are part of companies' balance sheets. After the collapse of Lehman Brothers, international trade declined by 30% (Dooley and Hutchison 2009).

The loss in equity value forced banks to recapitalise, that is, financial institutions started restraining credit and keeping capital in order to cover for the losses in asset value. The contraction of credit forced enterprises to cut back on output and employment (Lapavitsas 2009), leading to an economic slowdown worldwide.

The high integration of financial markets and the distribution of risk to virtually all structured financial products explain why the crash of the subprime mortgage market triggered a worldwide financial crisis. The collapse of financial institutions considered "too big to fail" called for the intervention of governments, as lenders of last resort. This mechanism resulted in yet a third normalisation, where the distinction between private and public debt was lost.

"The crisis paralysed the financial system and progressively disrupted real accumulation. Central-bank intervention has been pervasive but not decisive, forcing governments to intervene to rescue banks and ameliorate the recession" (Lapavitsas 2009: 124). Four years later, the crisis turned into a sovereign debt crisis as systemic risk had been passed on to governments not prepared to support the bail out of such big institutions. Ireland in 2010, Portugal and Greece in 2011, have all received bailout packages from the European Central Bank and the International Monetary Fund as they had no access to bond markets because their spread was too high.

Ratings played a central role during the crisis, as they were “the sole source of information for marking-to-market” (Gorton 2008: 58). Rating agencies base their evaluation of private and governmental institutions on interviews, published data, balance sheets and declared intentions. This mechanism strengthens the link between economic performance and politics. Once governments start acting as implicit loan guarantees in financial markets, confidence on state bond performance comes to depend more closely on political stability and the ability to carry out and implement long term plans.

The need to maintain market confidence is not a new phenomenon. Since the abolition of the gold standard, the value of national currencies has been determined by how economies are perceived internationally, rather than by the amount of trade going on (Douthwaite 2000). What distinguishes the current sovereign debt crisis is the fact that governments themselves do not have the means to measure nor locate their debt. Furthermore, within the European Monetary Union the value of the currency is established at the European level, and does not reflect the perceived trustworthiness of each individual country using it. Ratings in this context come to substitute the role previously held by national currencies.

European economies were particularly vulnerable to the crisis, as the financial sector was an important contributor to GDP, accounting for 29.3% for the EU-27 in 2010 (Eurostat 2012). Financial institutions considered “too big to fail” took on too much risk (Stigliz 2010) and had to be rescued by governments. McKinley (2011) argues that the government bailout of Bear Sterns, the first US bank to fail in 2007, led the market to believe that other institutions, including Lehman Brothers, would also be rescued if needed. Following the bailout logic, corporate CDS (private debt) was substituted by sovereign CDS (public debt). This normalisation mechanism made possible the interchangeable use of public and private debt. Investors turned to risk-free assets, such as solvent sovereign bonds. However, as the crisis took on a dimension that was too big for governments to guarantee, the very solvency of sovereign states started to be questioned. The ratings of governments were downgraded. The financial crisis developed into yet another dimension, turning into a sovereign debt crisis.

The impact of the economic slowdown was especially felt in the European periphery, or what are known as the PIGS (Portugal, Ireland, and later Italy, Greece and Spain). I argue that the economic crisis that PIGS are experiencing is aggravated by the single currency. The European Monetary Union (EMU) brought huge benefits to those countries that previously had to pay higher interest rates to borrow in the market (Issing 2011). The EMU enabled member states to access cheap financing, thanks to the market's confidence in the new currency, without solving the underlying imbalances or fiscal deficit problems. At the same time, the EMU binds different economies to a single monetary policy, so that currency devaluation and other policies that were generally used to deal with current account or fiscal account deficits could no longer be used by individual countries.

This situation can be described as the 'open-economy trilemma', that is, "countries cannot simultaneously maintain independent monetary policies, fixed exchange rates, and an open capital account" (Rodrik 2000: 180). The European Central Bank (ECB) regulates the currency, whereas fiscal policies are left to individual countries. "The fact that the peripheral eurozone countries could issue debt in their own currency appears to have allayed fears regarding currency mismatch problems as well as contagion effects; nevertheless, the consequences of the inability of the peripheral euro zone countries to exercise an independent monetary policy were ignored" (Katsimi and Moutos 2010). The boundaries imposed by the EMU aggravated the consequences of the loss of information caused by normalisation, depriving the PIGS of the means to deal with the crisis and forcing a shift of decision making to higher level players, that is the European Central Bank, the IMF and the European Union.

As a consequence, the impact of the global financial crisis was distinctively different in Ireland and in the UK, for example. Whereas the UK responded with a loose monetary policy that led to a devaluation of the British pound, Ireland could not pursue an independent monetary policy and witnessed a sharp increase in sovereign debt and unemployment (Mushin 2010), eventually leading to an internal devaluation by means of prices and wages.

Greece entered the EMU with a higher budget deficit than that posed by the Maastricht Treaty as the limit. Thanks to its imminent entrance into the eurozone and the market's consequent belief in the realignment of European economies through the monetary union, its government had access to cheap financing, and it temporarily eased its debt and was accepted into the EMU. The entrance into the monetary union allowed for a temporary alignment of the ratings of member states and normalised borrowing conditions.

The blurring of information in favour of ratings on intentions and expected market stability undermined the capacity of the peripheral European economies to react to financial crises from the start. Greece's economy was characterised by excessively large public spending and an almost exclusive reliance on the tourism sector as a source of revenue. It follows that government borrowing sustained economic growth, without an increased productive capacity and even without any adjustments in public spending. "In 2009, Greece hit a budget deficit – the difference between state spending and tax receipts – equivalent to 15 per cent of GDP, bringing total government debt levels to €300 billion, the equivalent of 127 per cent of GDP" (Mullan 2011). The financial crisis and the consequent crisis of confidence in financial instruments precipitated the country's ability to borrow on financial markets and destroyed its means to repay its debt.

Another example is given by the Spanish case. Spain witnessed a housing bubble similar to that of the US, and a similarly spectacular spike in house prices led to increased lending by banks, expecting high returns on investment. The liquidity need of banks led to increased loan securitisation (the second normalisation) as a way to raise more funds, resulting in an increased issuance of asset backed securities from 3 billion Euros in 2008 to 16 billion Euros in 2009 (Carbó-Valverde et al. 2012). Construction and real-estate loans accounted for 43% of GDP in 2009 (IMF 2012).

The financial crisis made it impossible for real estate companies to service their loans. Insolvent real estate agents thus had to give away unsold property to the banks, which were thus exposed to losses in real estate value themselves and started restraining credit. Additionally, Spain was particularly vulnerable to the contraction of credit caused by the crisis as a high share of investment was funded from abroad. Once the crisis started, this inflow of money stopped and aggravated the domestic recession. The dimension of the crisis forced the government to step in and rescue the "too big to fail" players, turning private debt into a sovereign debt crisis (the third normalisation) and coming to rely exclusively on ratings to overcome the complete loss of information.

The above cases are yet another example of how reliance on scientific information and expert knowledge (in the form of ratings, economic models and risk estimates) may in some cases lead to an increase in uncertainty. In the case under study, increased uncertainty is due to the fact that the systemic loss of information was masked under the apparent robustness of economic models and of economic growth.

The financial crisis of 2007-08 took the world by surprise. Since the 1970s, financial crises had taken the form of small and manageable events, so that financial experts grew increasingly confident of the resilience of the overall financial system (Gamble 2014). I argue that part of this confidence can be attributed to a poor handling of the uncertainty and complexity of the system, due to the reliance on oversimplified information for the governance of the financial market. The ratings and economic models used are not consistent with the goal of maximising profit in the long run, revealing the limited usefulness of the scientific information used.

3. Multiple descriptive domains

The fact that the financial crisis was unexpected raises doubts over the pertinence and usefulness of the models and representations used to analyse the financial market and its relation to the economy. This section provides an analysis of the epistemology of neo-classical economics and its use in the governance of the economic system. I present the two different descriptive domains used in economics and relate the representations of the economic system derived from these descriptions to the (poor) governance of the financial sector.

Economics as a discipline is composed of two descriptive domains, microeconomics and macroeconomics. A descriptive domain is a particular description of the system determined by a specific "choice of mapping only a certain set of its qualities/properties" (Giampietro 2002: 247). In other words, the numerical assessment used to describe a system reflects not only the characteristics of the system but also the goals and beliefs of the analyst, which explain the apparently arbitrary choice of mapping in a certain way only certain characteristics considered more relevant than others (Ibid).

Microeconomics looks at the individual scale, and is concerned with end-means utility maximisation in relation to consumers and profit maximisation in relation to firms (Gravelle and Rees 2004), in a context of modest scarcity. The analyst chooses to describe human behaviour in terms of rationality. Microeconomics simulates the exercise of a psychologist, albeit with a very narrow understanding of cognitive processes (Kahneman and Tversky 1982): it describes human behaviour in terms of rationality and measures utility, risk aversion, and preferences.

Macroeconomics deals with a different scale of analysis, looking at the national level, and is concerned with the "structure, performance and behaviour of the economy as a whole" (Snowdon and Vane 2005: 1). Macroeconomics resembles more an accounting exercise, it tackles the question of how to characterise and measure the size of the economy defined through various expected aggregate balances: trade balance, fiscal balance, equilibrium employment and so on.

Macroeconomics measures the system as a whole and is concerned with aggregate output and employment, while microeconomics describes the workings of the sub-systems, that is, the individual consumer and firm through allocation, production and distribution. The two descriptive domains deal with non-equivalent scales, and need an analytical framework that can move across different scales and relate them to each other.

Economic theory, however, does not deal with the change of scales and uses the same theory for both micro and macro analysis (Solow 2003). This inconsistency has been characterised as "theoretical schizophrenia" (Greewald and Stiglitz 1987; Snowdon and Vane 2005).

Keynes's attempt to introduce a different descriptive domain for macroeconomics was successively reduced to the application of micro theory to macro analysis through the neoclassical synthesis of Keynes, resulting in the IS-LM model. "Keynesian macroeconomics and orthodox neoclassical microeconomics integrated about as well as oil and water" (Snowdon and Vane 2005: 21), precisely because they deal with non-equivalent descriptive domains.

Successive developments resulted in the New Classical approach, attempting to adapt macroeconomics to micro foundations, and New Keynesian theories, trying to adapt micro to macro economics. Both schools of thought neglect the issue of scale altogether by reducing the analysis to one dimension: micro for the New Classics and macro for the New Keynesians.

The reduction of the social to the aggregate of individuals fails to describe social relations, structures, power, conflicts and meanings (Fine 2002) and fails to acknowledge the incommensurability between the two descriptive domains. Condorcet and Arrow both contributed to showing the difficulties and theoretical challenges involved in modelling social behaviour as an aggregate of individuals. The Condorcet paradox demonstrates how collective decisions do not always result in consistent preference ordering (Munda 2005), so that at the societal level it makes more sense to talk about procedural rather than substantive rationality (Simon 1978).

Arrow's impossibility theorem demonstrates that social preferences cannot be defined without violating transitivity or non-dictatorship and speaks of "a 'democratic paralysis', a failure to act due not to a desire for inaction but to an inability to agree on proper action" (Nath 1969: 136). Notwithstanding the impossibility of defining the social optimum, social welfare theory assumes that individual preferences determine the socially optimal allocation of resources through the market mechanism.

The concept of pluralism introduced in chapter 1 is an alternative to the ideal of social optimum. Social optimum is based on the premise that individuals can agree on a single criterion of quality, defined in substantive terms. By taking a sceptical stance in relation to the possibility of defining an optimal solution, pluralism invites to the consideration of multiple criteria and to a procedural and epistemic quality assessment.

Overlooking values and decisions taken at the individual level also fails to explain the emergence of properties at the social level (Prigogine 1986). Simon's parable of the watchmakers offers a great example of how the different assembly procedures (at the micro level) adopted by two watchmakers produced watches of the same quality (at the macro level) but ultimately led one of the watchmakers to go out of business (Simon 1962). Similarly, an analysis of the financial crisis at the macro level may overlook the effect of greed and corruption and of the disappearance of social values such as guilt and shame at the individual level in the name of profit maximisation and economic growth, which supposedly translates into wealth creation for society as a whole.

The theoretical gap is difficult to overcome because micro and macroeconomics deal with different scales of analysis. Individual behaviour and social behaviour cannot be compared or measured using the same tools. Viewing the social as a system implies that the whole is more than the sum of its parts, that is, the interactions among the parts determine the properties of the whole (Simon 1962). In the social context, the individual's rationality is influenced by a variety of factors ranging from reciprocity, to reflexivity, solidarity, competition, and etc. (Polanyi 1957; Singer 2002).

The problem of how to move across non-equivalent descriptive domains, when moving from the micro to the macro scale, is simply ignored by methodology. Basing macroeconomics on micro foundations results in an accounting exercise precisely because it does not recognise society as a different concept from the sum of individuals and proceeds to add up and balance aggregate savings and aggregate investments, imports and exports, government spending and taxes. The economy is treated like a black box: what happens inside the economy is irrelevant, so long as inputs come out as outputs at the other end of the line. Adapting microeconomics to macro theory, on the other hand, ignores the implications of moral hazard and asymmetric information on a large scale.

The challenge consists in the impossibility of representing a complex object in simplified terms without losing relevant information (Giampietro et al. 2012). If one accepts this point, the definition of what is to be considered relevant depends on the goal of the analysis. In other words, pre-existing value judgements determine the scope and goal of the analysis, which is thus subject-dependent. Different subjects will describe the observed system differently, gather different information and conduct different analyses according to their perspective. Therefore, the existence of a plurality of relevant narratives to describe the observed system reflects the existence of a plurality of legitimate perspectives found among social actors.

The critical point is to decide who has the power to impose a set of useful narratives. The choice of a relevant narrative determines the useful perceptions to be taken into account when generating models or indicators. In the context of the global financial crisis, the dominant narrative has been that of maximisation of financial capital, which led to the financialisation of both private and public assets and to a monologic accounting of value. This hegemonic narrative is based on a reductionist representation of reality, based solely on risk indicators, which led to a drastic reduction of information and deprived financial actors of the means to deal with the crisis.

An alternative interpretation can be drawn from hierarchy theory. A hierarchical system is a system composed of interrelated subsystems, which interact in a non simple way (Simon 1962). The economic system can be understood as a hierarchical system, composed of the macroeconomic system and its interrelated subsystems at the micro level: economic agents, firms, banks, insurance companies, etc (Figure 4). The two sub-systems, the individual and the firm, exchange labour and wages, and they interact with the whole economic system through demand and supply (flows of goods and services) and savings and investments (monetary flows). The economy also relates to the international financial market through monetary flows.

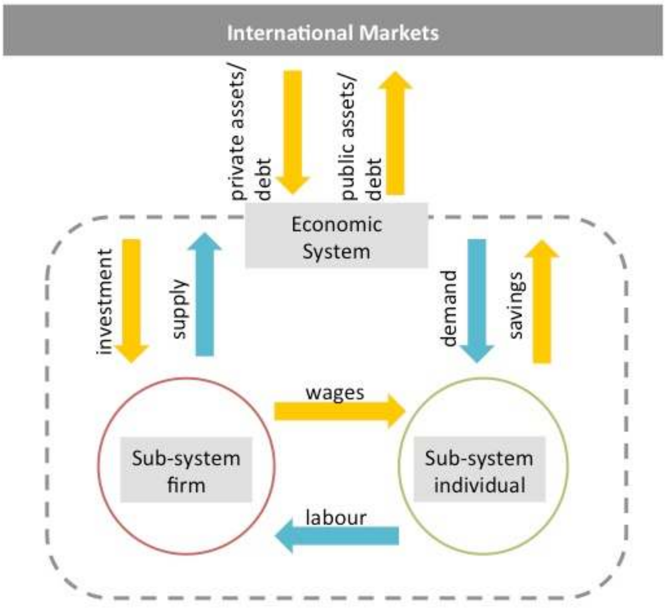

Figure 4. The economy as a hierarchical system. Source: Kovacic 2013.

Within the narrative of economic analysis, the crisis can be analysed at two levels. At the micro level banks started lending money to risky borrowers. If the borrower does not repay their loan, the bank loses money. As a protection against default risk, banks charge interest on loans, so that the overhead they gain through those borrowers that honour their debt covers the money lost through the borrowers who default.

At the same time, the bank borrows from investors in order to finance its loans. Investors gain a share of the interest earned on loans, which depends on the length of the contract and on the risk involved. Higher interest is paid on riskier assets. The investor may lose on a high risk operation. Through this mechanism a higher default risk is passed on to the investor. The bank acts as a rational profit maximising agent.

Normalisation deprives the banking system of the information needed to set interest rates against estimated risk and it can no longer act as a rational agent. The main problem is that this simplification does not deal with multiple scales. Both moral hazard and the principal-agent problem arise as the result of asymmetric information, which in turn affects the ability of the agent to act rationally at different scales of analysis. Diluting risk may be a rational choice at the individual level (from the point of view of the financial agent) but it causes widespread instability at the market level (from the point of view of the financial sector). Once information loss becomes a systemic problem, the size and location of risk and uncertainty are unknown to all agents and individual rationality does not suffice to stir the market.

At the macro level, the banking system stabilises monetary flows. Banks lend money to firms and collect savings from capital owners, investors and the labour force. At equilibrium, aggregate savings equal aggregate investments. Different economic theories disagree on the direction of causality between aggregate savings and aggregate investments. In neo-classical economics, the banking system lends what they have as assets, so that savings determine investments. According to Keynes, investments finance productive activities and thus generate jobs, so that investments determine savings (Verdon 1994).

Either way, banks serve as regulators of the flow of money channelling funds from savings to investors. From this point of view, the representation of financial institution as rational economic agents is inconsistent with the analysis of their role in the macro economy. The representation of the economic system provided by neo-classical economic analysis thus presents a serious problem of quality in relation to the science-policy interface. Even though economic models are mathematically sound, the representation of financial institutions provided by microeconomics is not consistent with the scale of analysis used to describe the crisis (the overall system). This is a problem of pertinence.

Financialisation (the conversion of all sorts of funds to financial assets) is a way to boost investments artificially, independently from savings, by treating mortgages, salaries, pension funds, and insurance premia as savings. Investments no longer serve to boost productive activity but are re-injected into the financial system through the ascending passage from MBS to CDO to CDS illustrated above. In engaging in financialisation, the bank stops acting as a stabiliser of economic flows, starts fuelling an upward spiral of virtual accumulation aimed at self-inflation and the system goes bust.

The changing function of financial institutions at different scales of analysis can be explained through the concept of "holon" (Koestler 1969). "A holon is a whole made of smaller parts (e.g. a human being is made up of organs, tissues, cells, atoms) and at the same time it is a part of a larger whole (an individual human being is part of a household, a community, a country, the global economy)" (Giampietro 2002: 251). The concept of holon is useful in order to handle different descriptive domains – in terms of the pre-analytical choices of space and time – according to the functions one wants to study.

When observed at different scales, the same system can be perceived as interacting with its context in different ways under different identities (Giampietro et al. 2006). At the micro level, banks act as profit maximising economic agents, whereas at the macro level financial intermediaries play a role in stabilizing the flow of capital. The function of financial institutions changes depending on the scale adopted. Therefore, the stability of the financial sector at the national scale cannot be left to the (supposedly self-regulating) interactions of financial agents at the individual scale. The economic narrative and models used to describe the crisis (looking for a single identity of the system) fail to capture the different functions that the financial sector plays at different scales.

The fallacy of dealing with non-equivalent descriptive domains helps explain why economists cannot agree on what caused the financial crisis (Lo 2012). Risk was introduced into the economy at the micro level, as individual mortgages, as individual securities, as individual insurance claims. At a larger scale, the system is infected with different types of risk referring to different economic activities controlled by different economic agents, but the characteristics and location of this risk is now unknown. There is no control over what happened inside the black box. The blurring of different scales of analysis is a consequence of a series of normalisations that deprived the economic narrative of the means to generate a meaningful representation of the financial crisis.

The acknowledgement of the existence of different hierarchical scales within the economic system sheds light on the emerging properties (instability) of the system as a whole in relation to the interactions among its parts (blurring of information and dispersion of risk). Minsky's financial instability hypothesis hinges precisely on the fallacy of composition at the macro level of risky choices at the micro level (1992). Instability in the system derives from the fact that money is endogenous, that is, it is created "as a result of meeting the 'needs of trade'. When firms wish to invest they call upon the banks to borrow the required funds, and in the process money is created" (Arestis 1996: 22).

The interaction between scales can be described through a transmission mechanism that has as its basis the narrative of capital accumulation as the common good to be achieved, which translates in the legitimating of values such as greed and practices such as shadow-banking at the individual level. Economic growth has gone from being a means to an end, a way of providing society with better living standards, to being an end in itself. Within this discourse, a growing economy becomes the "goal to which human labour and lifestyles must adapt" (Porter et al. 1980: 17) and rent-seeking behaviours come to be seen as rational and socially acceptable. Unregulated banking practices created a wide range of financial derivatives that distributed risk to the financial market as a whole while destroying information. As a consequence, at the macro level the system becomes unstable. The transmission mechanism across different scales is represented by Figure 5.

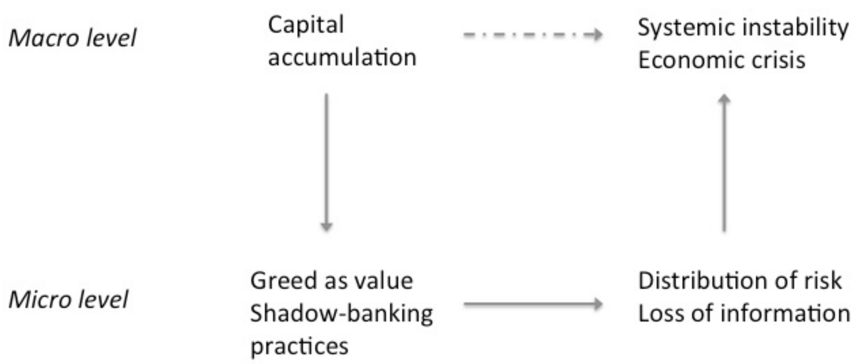

Figure 5. Transmission mechanism across multiple scales of analysis. Adapted from Bunge 2000. Source: Kovacic 2013.

This analysis shows that, although corruption, greed, collusion between private financial institutions and governments, asymmetric information and conflicting interests were all part of the malfunctioning of the financial sector, there is also a need for a better understanding of complexity and of the limitations of simplified representations of the economic system in guiding action and policy. The multi-scale analysis of the economic system is one way of identifying the uncertainties in the system and of evaluating the pertinence of the representations used.

4. The crisis of the economic paradigm

This section is devoted to unresponsiveness of the neo-classical economics knowledge base to the financial collapse and of the subsequent poor management of the economic crisis. I attribute the inadaptability of the economic paradigm to the oversimplifications and to the excessive mathematical formalism of economics, which produced representations of the economic system that are too general to account for specific conditions (and, therefore, to be applied in practice) and that are immune to feedback from experience. From this point of view, the usefulness of the representations of the economic system is brought into question, as the goal of maximising profits, or even of maintaining the system, is not reached.

I refer to economics as a paradigm following Kuhn's definition of paradigm as "universally recognised scientific achievements that for a time provide model problems and solutions to a community of practitioners" (1962: viii). More specifically, Kuhn identifies two achievements that define a paradigm: (i) a paradigm is a locus of scientific commitment, which attracts "an enduring group of adherents away from competing modes of scientific activity" and (ii) it is "sufficiently open-ended to leave all sorts of problems for the redefined group of practitioners to resolve" (1962: 10). In other words, a paradigm does not need to offer answers to all questions, but acts rather as an umbrella under which to organise fact gathering.

Economics complies with both requirements. The economic community shows a high level of commitment to the theoretical tools and to the approach of economics (Gamble 2014), which is seen as useful to frame a variety of very different problems, such as the evaluation of ecosystem services in environmental economics, and the modelling of psychological and social aspects of individual decisions in behavioural economics.

The commitment to the discipline can be seen both (i) in the continued use of GDP in the composite sustainability indicators produced following the "Beyond GDP" conference of 2007 (EC 2009), and (ii) in the continued reference to economics as a framework in very different sub-disciplines such as Marxist economics and neo-liberal economics.

At the same time, economics is sufficiently open-ended to allow for a variety of debates within the discipline to take place over, as mentioned above, the handling of multiple scales ranging from individual behaviour to economic growth, as well as the evaluation of commodities for which there are no markets (such as pollution, biodiversity, the value of future generations).

I argue that the financial crisis is reflected in a crisis of the economic paradigm, that is, in an increasing scepticism over the explanatory power and the universal applicability of the discipline. Illustrative of this attitude, Silva and Lorite Escorihuela (2013) see the European sovereign debt crisis as a failure of economic remedies.

The irreducible uncertainty that characterises modern economies created a new language, which conveys intentions rather than accurate information. The new language is that of insurance risk, of bond spreads, of differentials between declared intentions to borrow and to lend. The concept of risk has become prominent in public discourse (Lapavitsas 2009). The spread, for example, is a measure of the difference between a bank's, or a government's, borrowing costs and interest rate on lending, the latter being set so as to cover the estimated default risk of borrowing. As risk increases, so does the spread in order to gather enough capital through interest rates to cover higher borrowing costs. Interestingly, the technical language of investment banking has been adopted by the mass media. Italian, Portuguese and Spanish newspapers started using the term "spread," in English, in order to evaluate the performance of the government *vis-a-vis* the financial market. However, no definition of spread is presented. It is simply assumed that the layman understands the language of finance, or else that the media just pass the parcel on, without unwrapping it for the readers in an attempt to explain the inexplicable.

The emerging technocratic discourse is based on two underlying assumptions: that the country's interests coincide with the interests of big financial corporations, the "too big to fail" players, and the assumption that technocrats are apolitical agents, pursuing the common good. Economic growth is assumed to be valid independently from the social context. The technocratic governments established in Italy and, for a shorter period of time, in Greece are representative of this tendency, and are portrayed as neutral caretakers replacing the elected governments while politicians reach a settlement.

Brown (2009) talks of monologic accounting, defined as a situation where pre-given values centred on the need of finance capital are assumed to benefit everyone, regardless of their political standpoint. Funtowicz and Ravetz (1990) explain this process as a hegemonisation of narratives. The privileged position of technicians comes from the conception of science as a uniquely privileged vehicle to truth (Demeritt 2001), or, like Icarus's wings, capable of carrying society in a sphere that is "free from chance, prejudice, and arbitrariness" (Ezrahi 1990: 3). Expert knowledge is seen as a depoliticised, neutral tool, which is divorced from social reasons and reads as a view from nowhere (Nagel 1989; Shapin 1998).

The formalisation and mathematisation of economics, and of financial economics in particular, "as manifested in the transition from political economy to economics, [has led] to an almost brand-new scientific body totally detached from its historical and social setting" (Fine and Milonakis 2011: 11). The tendency towards technocracy is evident in the preference of the financial sector to hire physics and mathematics graduates (Ibid). Fine and Milonakis (2011) argue that, as a result, economics is "useless but true," that is, mathematically valid but void of any practical relevance.

The subordination of real to fictitious capital (Fine and Milonakis 2011) has increased capitalisation, reduced liquidity and transformed all sources of revenue – from salaries, to pensions, insurance funds, and so on – into financial products. That is, purchasing power went from being based on income to being guaranteed by investment banks based on expected future income. This process has come to be known as financialisation (Lapavitsas 2009; Fine and Milonakis 2011). The consequence was a drastic drop in personal savings in the 2000s (Lapavitsas 2009). By turning all sorts of capital, real and fictitious, into financial products, the fact that banks were lending money they did not have and borrowing capital they could not pay back went unnoticed. The reductionism of finance proved extremely useful for this disguise.

The use of mono-scale and mono-dimensional models ties the analysis to a static description. A model can be thought of as the formalisation of a given perception of the observer (Rosen 1985). The analyst defines which variables are relevant to the model (how to encode relevant attributes of the observed system) according to their pre-analytical understanding of causality. Technical knowledge also requires pre-analytical choices over the definition of relevance (what should be observed and how) that are normative in nature and undermine its supposed neutrality. Semantic choices define the direction of causality and the categories used to build the model (Giampietro 2002). The argument over the direction of causality between investments and savings is precisely a result of the clash between different narratives using semantically closed categories. The models used are unable to explain investments as independent from savings, and to recognise them as a tool used to inflate national accounts.

5. Conclusion

I have argued that the crisis spread because of a dispersion of risk from individual assets to the whole financial system, due to the decomposition and restructuring of debt into a variety of financial products. The financial crisis affected the real economy due to the vanishing distinction between assets and debts first, enabled by securitisation; and between private and public debt secondly, due to the increasing overlap between political and financial interests. “The crisis paralysed the financial system and progressively disrupted real accumulation” (Lapavitsas 2009). The dispersion of risk to the whole of the financial market set the basis for the rapid contagion of the crisis to markets on a global scale and ultimately required government intervention to restore confidence in the market itself.

The persistence of the European sovereign debt crisis and the lack of confidence in financial markets go beyond the problem of risk management. It questions the legitimacy of technocrats and experts to guide decision making in the presence of uncertainty. As the financial crisis clearly demonstrates, the use of numerical ratings and indicators “creates an illusion of a degree of precision that in many cases is not supported by the input data" (VDI 2000: 29). Irreducible uncertainty means that experts cannot know how to manage and steer the crisis.

Hierarchy theory offers some insights that can help move beyond the reductionist paradigm. In particular, the concept of holon is used to stress the importance of considering multiple scales in the analysis of economic systems and the changing function of financial intermediaries across scales. Such analysis highlights the emergence of a systemic instability at the macro level caused by the rational response of financial institutions to the opportunities for speculation offered by exotic financial derivatives at the micro level. That is, the interactions between the parts (i.e. the reduction of risk by distributing it to various financial products) led to a non-linear transmission of risk and loss of information that ultimately deprived the system as a whole of the means to solve the crisis.

In the context of irreducible uncertainty and in the presence of a plurality of different legitimate values (Funtowicz and Ravetz 1993), technical knowledge cannot supply an objective, or optimal, solution to the problem, as in a puzzle-solving exercise (Kuhn 1962). The failure of the conceptual instruments used by the economic paradigm, especially normalised risk indicators, suggests that there is a need for a quality assessment of quantitative indicators to be used for governance.

As I have shown, the information used (ratings, risk estimates, economic models) fails to satisfy the two criteria used for quality assessment, pertinence and usefulness. In terms of pertinence, there is a lack of congruence between the representations of economic agents and the scale of analysis used to explain the crisis. In terms of usefulness, the indicators used to guide individual decisions failed to provide the expected gains to the economic agents using them. As a result, the complexity of the economic system was not taken into account leading to a poor governance of the proliferation of structured financial products and of the crisis itself.

Chapter 3

Case study: The societal metabolism of water in Israel.[4]

1. Introduction

Water management in Israel is a highly contested topic, which generates interest from a plurality of perspectives. The Israeli government sees water as a scarce resource that is crucial to maintain living standards and ensure the well being of the population (Ministry of Foreign Affairs 2011; Ministry of Environmental Protection 2009). Water scarcity has prompted the adoption of the most efficient water systems in agriculture and an unparalleled level of innovation in the country, ranging from drip irrigation, grey water recycling in agriculture, all the way to the development of sea-water resistant crops (Negev Foundation 2010; Yella Reddy 2008). Water has been taken also as the explanatory factor for conflicts in the Middle East (Shiva 2004; Postel and Wolf 2001) and within Israel and Palestine (Alatout 2006). In this case study, I make use of an integrated assessment of biophysical and socio-economic factors to help generate a multi-scale representation of the societal metabolism of water in Israel and of the challenges of water management in this context.

The science-policy interface is analysed from the point of view of assessing the sustainability of water management. In this chapter, I analyse both documents and publications issued by the government and associated public entities, such as the state-owned water company, and documents published by private research centres, Israeli and non-Israeli academics, newspapers and international organisations such as the United Nations (UN). The science-policy interface refers to the governance of water related issues and I have considered policy relevant information in a broad

[4] This chapter has been adapted from Kovacic (2014).

sense as the collection of actors that influence, have a stake or participate in the debate about water in Israel.

This assessment of sustainability is a very clear example of the pluralism in the scientific knowledge base. Sustainability can be defined in a variety of different ways, often non-equivalent to each other. In order to make sense of the plurality of sustainability assessments related to water, I refer to the concepts of feasibility, viability and desirability. Feasibility is defined as the compatibility of the socio-economic system with the biophysical constraints posed by the ecosystem in which it is embedded. In this case, sustainability is assessed from a large scale of analysis and an external view of the system. Examples of sustainability assessment from a feasibility point of view include the maintenance of water bodies, biodiversity, ecosystem stability.

Viability is defined as the compatibility of the system with internal constraints posed by the organisation of society, such as the balance between working and dependent population, the monetary surplus required to sustain public health and education systems, the energy requirement of the productive sectors, and so on. From the point of view of viability, sustainability is assessed at the scale of society and includes the maintenance of the welfare system, the well being of future generations, living standards, *et cetera*. Feasibility and viability make it possible to check the pertinence of sustainability assessments across different scales of analysis.

At the same time, water management is an interesting case study in order to analyse the interplay of a plurality of value-judgments in relation to what is to be considered useful in the assessment of the sustainability of water management. In this case, I refer to the concept of desirability, defined as the compatibility of each representation with different social and cultural values. The discussion of desirability makes it possible to assess the plurality of value-judgements present in the Israeli society and in the literature related to the governance of water in Israel. The interest of this case study thus consists of both the pluralism present in the scientific knowledge base and of the pluralism in the governance of water in Israel.

I analyse water from the point of view of societal metabolism, in order to relate the analysis of the biophysical flows to the management of water and policy making. For this reason, the analysis is centred on the water flows that are under human control. Societal metabolism is a concept borrowed from biology to describe the integrated set of processes expressed by human societies using materials and energy to reproduce themselves (Giampietro et al. 2012). Extensive research shows that there is a strong correlation between the level of economic development of a society and the rate of energy and material consumption (Giampietro et al. 2012; Hall 2000). As societies move from hunter-gatherer to industrial economies, there is an acceleration in the rates of energy and material consumption both in extensive terms (more population) and intensive terms (higher consumption per capita). One immediate consequence is that more developed societies are more dependent on material and energy throughputs in order to maintain their lifestyles.

A higher metabolic rate of energy, food and other materials implies also a higher water consumption rate. This fact is of particular interest in the case of Israel, where water scarcity poses significant limits to the feasibility of the current metabolic pattern. I analyse water flows across different economic sectors in order to reveal how and in which ways water is needed to sustain societal metabolism.

The analysis contributes to the challenge of evaluating the pertinence of quantitative representations of sustainability when looking at complex systems characterised by different system definitions across scales. In this case, at the level of the ecosystem water defines the identity of the system (for example, a river), while at the level of society water is better understood as an input that makes it possible to reproduced specific societal functions (for example, agriculture). Scientific information can help assessing the viability and feasibility of the system under analysis as a means to support an informed debate with society at large over the definition of a desirable social organisation and over the handling of high levels of uncertainty. In this case study, many levels of uncertainty can be identified, such as technical uncertainty in the estimation of groundwater, methodological uncertainty in the estimation of precipitation, ignorance and indeterminacy with respect to future conditions, social tensions, external shocks due to financial or oil supply volatility.

I analyse water management in the State of Israel, not between Israel and Palestine. I use the definition of Israel and of the Israeli population given by the State of Israel. Both the definition of the territory and of the population are contested, and data estimates vary significantly depending on the sources. However, since the purpose of this analysis is to provide a set of tools to make sense of contradictory knowledge claims and not to provide an additional knowledge claim or an additional set of numbers, the controversy associated with the definitions used does not affect the results.

The second section looks at water extraction in Israel and gives an assessment of the feasibility of the current water consumption rate with relation to ecosystem constraints (the external view of the metabolism of the society, seen as a black-box, in relation to the biophysical context).

The third section relates water consumption rates to human activity and provides a quantitative description of the societal metabolism of water, characterising the viability of water use in relation to societal requirements (the internal view of the metabolism of the society, the utilization of water by the parts operating within the black-box) and in relation to land use, food and monetary flows in order to integrate biophysical and socio-economic variables.

The fourth section links the quantitative characterisation of water metabolism to the different narratives found in academic and policy documents, government and NGOs declarations, showing how the plurality of values and perceptions in society is reflected by a plurality of different representations of the problem. This raises the question: which representation(s) should be considered? Concluding remarks suggest that the debate over sustainability cannot be solved by science alone because it requires the discussion about the relevant scales, dimensions and social needs to be taken into account.

2. Water Resources – The feasibility check

In order to assess the scientific representations of water that are part of the water governance in Israel, I will first introduce the theoretical framework used to analyse water resources in general and then proceed to present the Israeli case study according to this framework.

Water resources can be classified as water available to human appropriation (surface and ground water, also defined as blue water) and water available to plants (soil water, also defined as green water), which can be used only in agriculture (Madrid et al. 2013). Blue water is appropriated by human activity, through water extraction and desalination, while green water can only be provided by the ecosystem, posing a severe constraint on the rate of water use (and water saving) in agriculture. Blue water can be further split according to its production cost into cheap water (e.g. water extracted through wells) and expensive water (e.g. desalinated seawater), which requires high technological, monetary and energy inputs. Blue water produced through expensive technologies is called economic water in this study. It adds to water appropriation but it implies an additional economic cost, and thus is not available to, say, a low income farming system. Therefore, the supply of economic water is made possible by the availability of economic surplus, and depends on the level of economic development of each society. Wastewater produced by human activity and discharged into the ecosystem (grey water) is not accounted for in this study.

A representation of water flows is given in the diagram below (Figure 6) following the grammar proposed by Madrid and colleagues (2013). The classification used allows mapping, in simplified terms, the interactions between the ecosystem and the societal system and the potential constraints to human appropriation of water resources. All figures refer to 2008. The value added of this diagram is that it presents at once different representations of water flows, making it possible to establish relations of equivalence between different perspectives and to link the biophysical assessment of water flows (at the ecosystem level) to the socio-economic classification used in the societal metabolism approach.

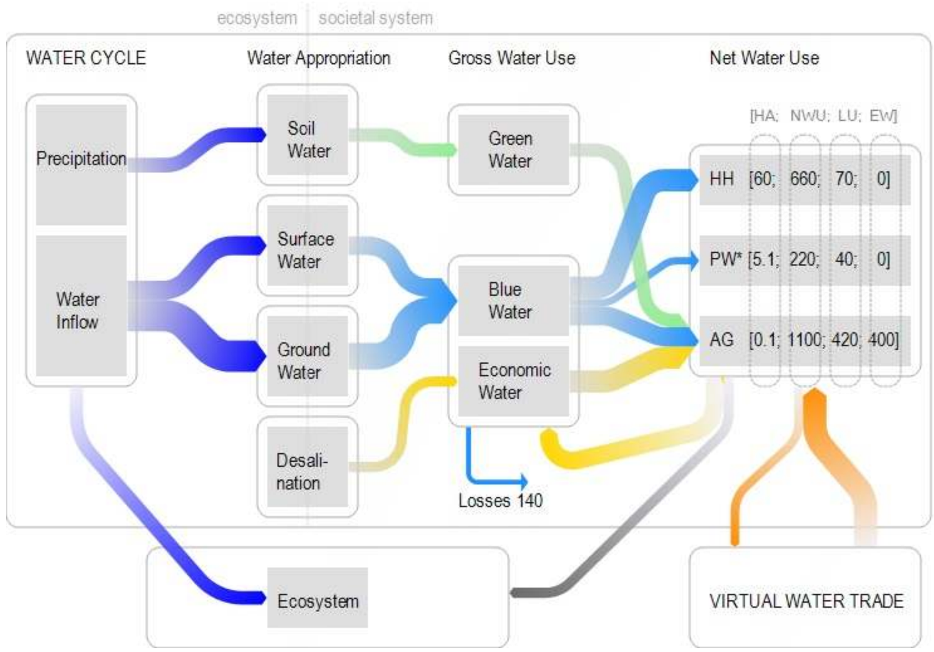

Figure 6. Water grammar. Adapted from Madrid et al. (2013). The economic compartments considered are Agriculture (AG), all other Paid Work activities (PW*) and Household/leisure and physiological overhead (HH). Values attributed to each compartment are Human Activity (HA) in million hours, Net Water Use (NWU) in million cubic meters, Land Use (LU) in thousand hectares, and Economic Water (EW) in million cubic meters. Source: Kovacic 2014.

Having set the theoretical framework used for the analysis of water flows, I now turn to the case study. Israel is characterised by an arid climate and chronic water scarcity. Average yearly rainfall ranges from 400 to 800 mm, and the Negev desert, where precipitation is down to 25 mm/year, accounts for about 60% of the area of the country (Sitton 2000). Water resources amount to 1.78 km^3/year (Aquastat 2011) including surface water and groundwater sources. Annual fresh water withdrawal is estimated to be about 1.54 km^3/year (Water Authority 2011), equivalent to 87% of total renewable water resources. The extraction rate of water resources is very high, in some cases threatening the stability of ecosystem.

For example, the main surface water source is the Kinneret Lake, situated in the North-Eastern border with Syria and Jordan, which receives its water from the Jordan River. The Kinneret Basin supplies about 25% of the annual water consumption in the country with 560 hm^3/year (Water Authority 2011). Water levels in the Kinneret Lake are lowering due to over-extraction of water, which occurred especially during the first years of the State. The lake used to supply 60% of Israel's water needs in the 1950s (Shiva 2004). In 2008 the Water Authority launched an awareness raising campaign entitled "Israel is going from red to black" (Haaretz 09/07/2008) indicating that the water level in the Kinneret was going from the red line, 213 metres below sea level, to the black line, 214.87 metres below sea level. Once the black line is reached, ecosystem instability and deterioration of water quality are so high that pumps in the lake can no longer operate (Ministry of Environmental Protection 2009). The limits imposed by the ecosystem are threatening the feasibility of the current water extraction rate.

The Yarkon Basin, or Mountain Aquifer, is the main source of groundwater extending from the West Bank to the Mediterranean Sea, and has an annual supply of 360 hm^3. The Coastal Aquifer contributes 240-300 hm^3/year with an area of 1,800 km^2, which includes Gaza's strip (Water Authority 2011). The two aquifers together are the second most important source of water in the country. The state exerts a tight control over water extraction given that both aquifers extend beyond the borders of the state and into Palestinian territories. Minor sources of water are found in the Eastern Mountain basins (80 hm^3/year), the Western Galilee basin at the border with Lebanon (140 hm^3/year), the Carmel Basin aquifer (40 hm^3/year), and the Arava and Negev desert aquifers (100 hm^3/year), which are very deep aquifers with no recharge and very high salinity (Water Authority 2011).

The feasibility assessment refers to the compatibility of the rate of water consumption by the Israeli society with the water provided by the ecosystem. Total water consumption, estimated at 2000 hm^3 in 2008, is considerably higher than what is provided by the ecosystem (1500 hm^3/year). This difference can be explained by three factors. Firstly, water desalination provided about 300 hm^3/year in 2008, from three plants: Ashkelon, Hadera and Palmahim. At the time of writing

(2015), there are five desalination plants in operation. Secondly, treated wastewater is re-used in agriculture, representing about 50% (530 hm3) of water inputs in this sector (Water Authority 2011), considerably reducing grey water production. Finally, in cases of extreme scarcity, fresh water has been imported from Turkey (Haaretz 05/03/2004).

Desalination and reuse of treated municipal water can be considered economic substitutes for fresh water (Allan 1999), that is, water produced thanks to economic surplus (represented as economic water in Figure 6). The limits imposed by the ecosystem are thus overcome through economic means and energy intensive technological solutions. As a matter of fact, water pumping uses about 5% of total electricity consumption (Water Authority 2010) and desalination accounts for an additional 10% (Haaretz 31/05/2014).

In response to growing water scarcity, the state has pursued active control over water consumption through a progressive tariff system, encouraging treated brackish water use for irrigation and limiting the use of high quality potable water; through subsidies for the adoption of water saving measures such as drip irrigation, water-efficient garden irrigation systems; and a highly centralised water and land management system, which are both considered public assets and allocated by quotas (Water Authority 2011). The Water Authority is responsible for monitoring water levels in the Kinneret Lake and the aquifers, and for establishing water quotas for the different economic sectors and agricultural practices. Mekorot, the state-owned water company, is responsible for the distribution of 70% of the country's fresh water and collection and treatment of waste water (Mekorot 2011). As a result, water consumption per capita has decreased but overall domestic water consumption in absolute terms has increased due to the nine-fold increase in population between 1948 and 2008 (see Figure 7).

Given that water use exceeds extraction, the current water consumption rate depends on water production external to the ecosystem. In terms of feasibility, Israel's water metabolism is unsustainable. The biophysical limit to water extraction is overcome through desalination, which in turn increases the country's dependence on fossil fuels. In other words, unfeasible water consumption patterns are sustained thanks to the monetary surplus generated by economic activity. Wealth can be seen as an energy surrogate (Allen et al. 1999). Israel represents a case of money for water, that is, societal overhead is invested in the production of water.

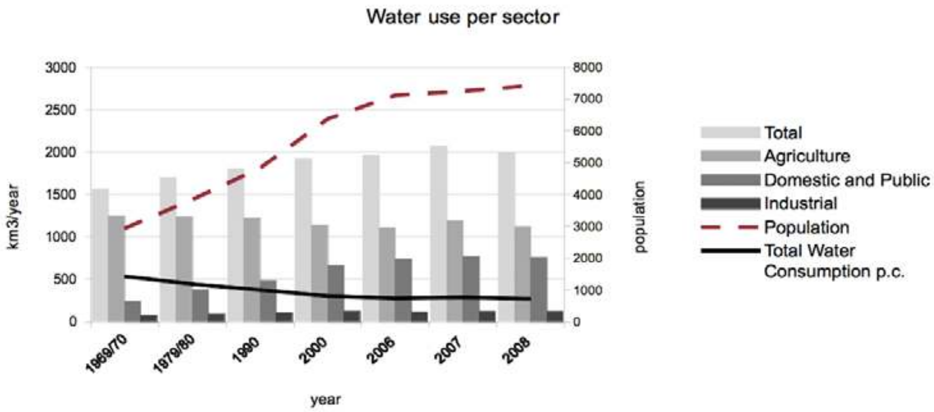

Figure 7. Water use per sector, water consumption per capita and population. Data taken from Central Bureau of Statistics (2011). Source: Kovacic 2014.

3. Societal Metabolism of Water – The viability check

I now turn to the internal view of society in order to understand how water resources are used and what determines total water demand. This scale of analysis makes it possible to assess sustainability from the point of view of viability. The concept of societal metabolism is used to explain how the system reproduces itself. This paper uses the Multi-Scale Integrated Assessment of Societal and Ecosystem Metabolism (MuSIASEM) approach (Giampietro et al. 2012; Giampietro et al. 2009), based on Georgescu-Roegen's flow-fund model. Funds are defined as elements that enter and exit the process with their identity intact – they remain the same in the chosen representation. In the study of economic processes, examples of funds are Ricardian land, capital and the work force. Flows are defined as elements that enter but do not exit, or exit without having entered, the production process. Examples of flows are: material inputs used in the production process, materials used for maintenance, output and waste (Georgescu-Roegen 1971). The flow-fund model consists in the representation of a process as the production or consumption of flows by a given fund. In the case under study, the set of functional and structural compartments of society represents the compound of fund elements to be sustained and water represents one of the flows required by society to reproduce itself. The funds describe what the system is and the flows describe what the system does interacting with its context in the chosen representation (Giampietro et al. 2012).

The novelty introduced by the MuSIASEM approach is the explicit use of fund elements. The identification of the fund is a pre-analytical choice used to set the context for the analysis of flows. According to this approach, the consumption (or production) of flows is aimed at the reproduction of the fund. This approach differs from economic analysis, for example, where monetary flows are analysed independently from the characteristics of the system generating them.

The flow-fund model is based on the consideration that the economic process "introduces qualitative change and is affected by the qualitative change of the environment into which it is anchored" (Georgescu-Roegen 1971). The economic process can thus be characterised by the intensity of resource use – i.e. flows of energy, water and materials per unit of fund elements. An analysis of the trends in the evolution of metabolic pattern shows that an acceleration in the rate of consumption of resources results in a higher societal overhead, which makes it possible for a larger share of the population not to work, allows the establishment of a welfare system, the creation of a wide variety of leisure activities, and so on (Giampietro et al. 2012).

In practical terms, societal metabolism refers to the accounting of different flows and funds according to the categories used to represent human activity, namely the different economic sectors and non-work activities. The analysis focuses on the fund element "human activity" measured in terms of hours per year. Total Human Activity is calculated by multiplying the population by 8760 (the number of hours in one year) and amounts to 65 million hours for the year 2008.

When considering the society as a whole (level n), its functioning cannot be described by disaggregating the whole into individuals, that is, in *per capita* terms. In order to study the hierarchical structures that constitute society one has to identify specific structural and functional compartments that define the characteristics of that society. At a lower level (n-1), human activity can be split between paid work (working activity in the conventional economic sectors) and non-productive activities (human activity outside the paid work sector). This split is determined by two facts: (i) only part of the population is economically active; (ii) those employed in the Paid Work sector work for only a limited amount of hours over the year.

The dependency ratio in Israel is 62%, which defines the fraction of the population that does not work. This category includes: children, the elderly, the unemployed, students, the military, and ultra-orthodox Jews. It follows that 38% of the population working a limited amount of hours per year (less than 2,000) sustains the consumption of the society as a whole, i.e. the non-working population and themselves. The average work load of the working population is of 35.4 hours/week (Central Bureau of Statistics 2011). Expressed in work hours per year, the human activity of the employed is approximately 5 million hours per year, representing 8% of Total Human Activity. This means that 92% of Total Human Activity in Israel is allocated outside the Paid Work sector.

The age group included between the ages of 16 and 64 years old is large due to the sustained immigration that has characterised Israel, especially during the first decades of the state. However, at the current fertility rate and with lower immigration, one can expect a progressive ageing of the population (a larger proportion of retired people) that will imply in the near future the need of re-arranging the current profile of time allocation (determined by dependency ratio, retirement age, unemployment rate) in order for the Israeli society to be able to sustain itself (Kovacic and Ramos-Martin 2014).

Coming to the analysis of water, the flow water corresponds to the total amount of human appropriated water, which includes only blue water in this study. Looking at the structural and functional compartments, the main consumer of water is the agricultural sector with about 54% of Net Water Use (Gross Water Use net of distribution losses). Israel's agricultural water consumption is markedly below the average for the Middle East (83%) and slightly below Mediterranean Europe (60%) (Aquastat 2011). This can be explained in terms of the advanced technology and high water efficiency that characterizes the agricultural sector in Israel. Thanks to the tight control over water use in agriculture and a switch to crops with higher yields (Felder 2002), water demand by this sector in absolute terms has slightly diminished during the last 20 years. Imports of high water requirement crops also help reduce domestic water consumption by externalising production (and the water use associated with it).

Given the importance of the agricultural sector in terms of water use, the analysis focuses on agriculture. Gross water use is allocated according to the use of the agricultural sector (52%), other Paid Work sector activities (10%), and the Household sector (31%), and accounts for water losses (7%) in distribution and handling. At this point, it is possible to compare the performance of the sectors considered in terms of metabolic rates, i.e. water consumed per hour of human activity, and economic productivity of water, i.e. dollars generated per m^3 of water used. The agricultural sector presents a metabolic rate of 11 m^3/hour, markedly above the remainder of the paid work sector (0.04 m^3/hr) and the Household sector (0.01 m^3/hour). This can be explained by the fact that agriculture requires more water than any other human activity and a very small portion of the work force is needed thanks to the high level of mechanisation of the sector. In terms of economic water productivity, the agricultural sector presents the lowest value added per m^3 of water (3 $/$m^3$), considerably below the average of the paid work sector (120 $/$m^3$). Agricultural exports perform slightly better (5 $/$m^3$) although this does not significantly add to overall Exports.

The allocation of water resources is determined by the specific function absolved by different human activities in the reproduction of the society. Different compartments mapping on to categories of human activities (Agriculture, Service and Government, Households) can be seen as different organs. Agriculture functions like the hearth, having a central role in the economic process because no other activity can provide food to society. For this reason, agriculture continues to be a priority area for the Israeli government (Haaretz 02/05/2008) despite the low economic productivity of the sector.

Just like the hearth requires the highest flow of blood, in the analogy agriculture is the sector which uses the most water resources. Water is necessary because it is a compulsory input for irrigation and technological innovation cannot reduce the biophysical water requirement of crops. For this reason, the agricultural sector in all countries is heavily dependent on water resources regardless of the level of economic development or technological progress achieved. This can be seen in the high water metabolic rate of the agricultural sector.

The concept of “strong” sustainability (Daly 1992; Brekke 1997) flags the impossibility of substitution of inputs made available by natural processes by capital and/or labour. The fact that agriculture contributes to a small share of GDP (about 2%) should not lead to the conclusion that society can reproduce itself without agriculture. At best, agriculture can be substituted by food imports, which only shifts water consumption somewhere else.

Imports of agricultural products relieve the pressure on the country's agricultural water demand. Allan (1999) termed the water savings derived from the import of crops as “virtual water” imports, in other words, the import of crops can be seen as the import of the water required to grow them. Israel imports 95% of its cereals, 80% of its fish, and half of its beef, oilseeds and nuts (Central Bureau of Statistics 2011). It should be noted that the own production of beef would imply a major boost in the demand for biomass production – an estimated 13 kg of grain are needed to produce 1 kg of beef (Pimentel and Pimentel 2003) – and in a high consumption of water for running the beef lots. The water saving through trade does not mean that society requires less water to survive, but simply that its requirement of water is externalised to the producer.

The agricultural activity that is maintained has moved more and more towards the production of high value added food products. Israel has specialised in the export of as citrus, avocado, and cherry tomatoes.

Given the interdependencies between different flows metabolised by society, such as water and food, and the corresponding funds characterising the system, such as the population and land use, I complete the discussion of the societal metabolism of water with an integrated representation of biophysical and economic variables.

Food and monetary flows are introduced in the analysis. Food is measured in Peta joules in order to account for the nutritional value of what is consumed. If one calculates food self-sufficiency ratio looking at the tons of food produced, one would find a value 72% for Israel. However, the nutritional value per ton of grains is quite different from that of fresh vegetables (mainly made up of water). For this reason, I use joules to quantify the nutritional value of food flows. In terms of joules, the food self-sufficiency ratio falls to 44%.

Two alternative approaches are used to represent societal metabolism (Table 1):

(1) The internal view – in the MuSIASEM approach, this view is used to categorise the end uses of funds and flows and characterise the organisation of society. I use human activity as the fund of reference in order to define the compartments for the analysis. The same structured is maintained for the fund land use and for the flows analysed. Water is allocated according to end uses and to the virtual water embedded in agricultural exports. Food is allocated to the household sector, losses and exports. Monetary flows represent Gross Value Added of each economic compartment, Taxes and Exports.

(2) The external view – in the MuSIASEM approach this view is used to show the dependence of the system on external inputs (imports or natural resources whose availability is outside human control). In this case, about 60% of food is imported from abroad, corresponding to 1700 hm^3 of virtual water imports. Virtual water is estimated as the water required to produce domestically the same amount of food imported, calculated using total water requirement of the current crop mix. Given that domestic production is specialised in crops with a low water requirement, virtual water imports are underestimated in this representation. Nevertheless, this assessment shows how food imports significantly reduce direct water use.

Table 1. Flows and funds of the system. The compartments considered are the Household sector (HH), the Paid Work sector (PW), the agricultural sector (AG) and other economic sectors within Paid Work (PW*). Source: Kovacic 2014.

INTERNAL VIEW	FOOD (million tons)	WATER (hm3)	MONETARY FLOWS (million $)	HUMAN ACTIVITY (billion hr)	LAND USE (thousand ha)
HH	6.6	660		60	70
PW		1300	158000	5.2	460
AG		1100	3160	0.1	420
PW*		220	150000	5.1	40
LOSSES	1.1	140	47000[1]		
EXPORTS	1.3	260 (v)	82000 (40%)		100 (v)
TOTAL	**9**	**2100**	**205000**	**65**	**530**

EXTERNAL VIEW	FOOD (million tons)	WATER (hm3)	MONETARY FLOWS (million $)	HUMAN ACTIVITY (billion hr)	LAND USE (thousand ha)
IMPORTS	3.5	690 (v)	85000 (42%)		260 (v)
DOMESTIC SUPPLY	5.6	2100	208000	65	530

[1]Taxes
(v) virtual

On the other hand, “Israel's clever “techno-fix” for the water crisis, desalination, is not the solution, since it is hugely energy intensive” (Haaretz 02/05/2008). Fossil fuels make up 98% of Israel's primary energy sources (UN 2002) and come entirely from imports (Central Bureau of Statistics 2010). In monetary terms, Israel presents a negative trade balance, indicating that the viability of the system in biophysical terms depends on the generation of economic surplus not directly related to biophysically based economic activities. Finally, in terms of land use, food imports also relieve the constraint posed by the limited availability of fertile arable land.

The value added of the MuSIASEM approach in this case study is that it makes it possible to extend the representation of the societal metabolism of water provided in section 2 (this chapter) and to include also monetary flows, food, human activity and land use. Thanks to this integrated analysis, I am able to take into account a variety of different representations related to the governance of water in Israel, which otherwise remain unrelated and often seem contradictory. For example, at the founding of the state, agriculture was of strategic importance for the government's proclaimed aim of food self-sufficiency, seen as a way of attracting immigrants. The analysis of food and land use is thus closely related to the complexity and the controversy surrounding water management in Israel.

It should be noted that Kibbutzim and Moshavim account for three quarters of the total area producing crops (Felder 2002). The latter are agricultural villages based on collective property and communal management (Simons and Ingram 2003). The Kibbutzim were the first settlements of Jews in Palestine, founded with the purpose of absorbing immigrants, providing settlement and defence, and are mostly located close to water sources in the Golan Heights and in the Jerusalem area. Those settlements have specialised in agricultural activities, with a distinctively local and autarchic character, and represent today the bulk of Israel's agricultural production.

The agricultural sector has thus developed as a result of a political lock-in. Since 1948, “the total area under cultivation has increased from 165,000 hectares to approximately 437,000 hectares … agricultural production has expanded 16-fold, more than three times the population growth” (UN 2002). However, the expansion of the agricultural sector is incompatible with the biophysical constraints posed by water and land availability and its viability is nowadays entirely dependent on the generation of a wealth surplus generated by other economic activities.

4. Social values and narratives – The desirability check

Is Israel a water scarce or a water abundant country? This may seem like an odd question given the aridity of the region. Nevertheless, in the early years of the State, “the country's annual water potential was a hotly contested category. Prior to Israel's establishment, the water potential of Palestine played an important role in determining the annual "appropriate" level of Jewish immigration" (Harris and Alatout 2010: 152). Zionist water experts argued that water resources were abundant in order to encourage open immigration of Jews into the country.

This debate introduces a new context to the question of defining the sustainable level of water use, namely social and cultural values. In order to assess the desirability of such a system, an in-depth participatory evaluation should be carried out with interested stakeholders. Different countries evaluate different problems differently, so that no general assessment of what is sustainable is possible in abstraction from the social and cultural context in which the assessment is embedded. The very concept of sustainability needs to be carefully defined according to the context. As a consequence, no conclusions can be drawn from the overview provided in this case study. What follows is a tentative approximation to some of the possible relevant criteria for evaluating the usefulness of the representations of the sustainability of water use in Israel.

The appraisal of the system as sustainable or unsustainable changes depending on the indicators used (e.g. efficient water use at the level of the agricultural sector versus the diminishing aquifer recharge rate at the ecosystem level), which in turn depend on the analyst's choice of representing a specific object in a certain way based on their goals and beliefs (e.g. encouraging immigration versus maintaining ecosystem stability). Desirability can thus be discussed by mapping the different indicators and representations found in the literature about water in Israel according to the temporal and spatial scales which they refer to.

Figure 8 offers an example of different sets of indicators that can be used to assess the three dimensions of sustainability (economic, social and environmental) at different spatial scales (ecosystem, society and the agricultural sector/individual economic agents) and temporal scales – the "snapshot time" (t1) at which the system is observed (static indicators) and the time differential (dt) used to simulate the dynamics of the system (performance indicators) (Giampietro 2003). The distinction among spatial and temporal scales is useful in order to avoid comparing "apples" with "oranges". Performance indicators such as GDP growth cannot be used as proxies for environmental indicators, such as water quality, because they refer to non-equivalent descriptive domains both in spatial and temporal terms.

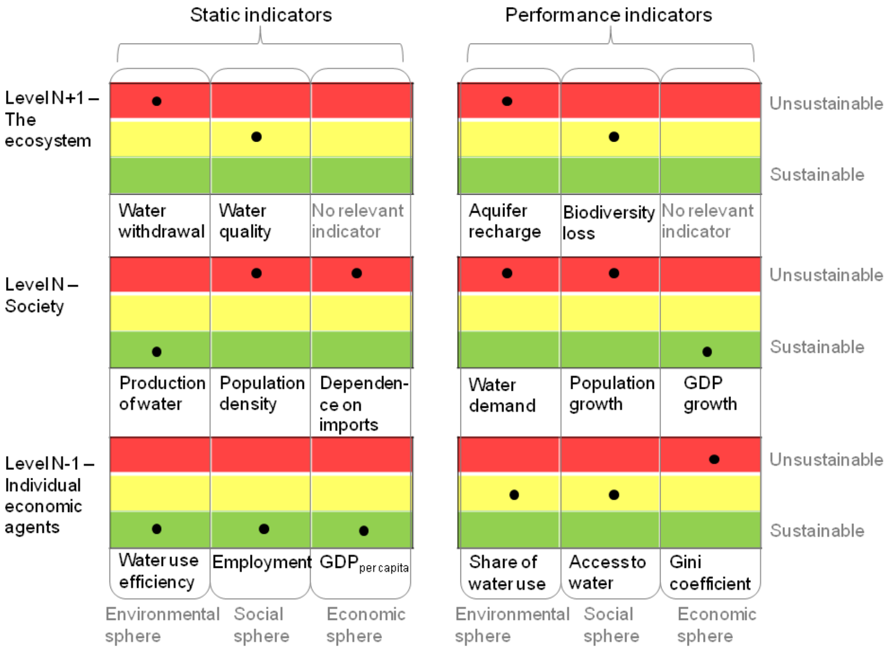

Figure 8. Sustainability indicators at different spatial and temporal scales. Source: Kovacic 2014.

The indicators identified are evaluated according to the narrative in which they are used. Narratives are defined as tools used to establish causality and assign meaning (Lyotard 1979). The classification of indicators as sustainable or unsustainable thus corresponds to the evaluation of that indicator according to the internal criteria adopted by each narrative. The usefulness of different indicators depends on what is considered desirable within a given narrative. For example, GDP growth can be considered useful within a narrative which prioritises economic growth over equality or environmental conservation.

The narrative of water scarcity, largely endorsed by the government, uses indicators such as water withdrawal rates, water quality (Ministry of Foreign Affairs 2011) and biodiversity loss (Ministry of Environmental Protection 2009) as well as the increasing water demand for the rehabilitation of aquifers (Water Authority 2010), which map onto the ecosystem level in the multi-scale representation. The "water crisis" narrative, classifying the current rate of water withdrawal as unsustainable, has been used as an argument to support centralised control of water and land (Harris and Alatout 2010).

At the level of society, different narratives can be identified regarding the current situation (time t): the capacity to produce water to meet society's demand is seen as a great achievement (Mekorot 2011), population density on the contrary is seen as a threat adding pressure on existing resources (Alatout 2006; UN 2002), and dependence on imports is perceived as a menace to energy and food security (Haaretz 02/05/2008; Centrel Bureau of Statistics 2010). Regarding the desirability of observed trends (time dt), growing water demand and growing population (Water Authority 2011) are seen as threats to sustainability, while GDP growth is considered as desirable (Ministry of Foreign Affairs 2011).

Zooming in at a lower level of analysis (Figure 8 includes both the agricultural sector and individual economic agents), the system seems to perform very well in terms of water efficiency (measured as water use per hectare (Negev Foundation 2010; Yella Reddy 2008)) and GDP per capita, which locates Israel in the high income countries category, as classified by the World Bank (2011). Due to the high level of mechanisation, the agricultural sector absorbs only 2% of the economically active population, a characteristic trait of more developed economies (Kovacic and Ramos-Martin 2014).

In a development perspective (adopting a higher temporal scale), the high share of water consumption by the agricultural sector poses a constraint to any further reduction in water demand since the biophysical crop water requirement cannot be reduced as seen above. Yet, the maintenance of the rural-agricultural sector is seen as a policy priority and the focus is shifted to the high domestic water consumption (Ministry of Foreign Affairs 2011). Concerns are raised over the unequal distribution of, or access to, water and income inequality. The Bedouin community in particular, whose settlements are not legally recognized, does not receive public services such as running water provision or sewage disposal (Shindler 2008). The

Gini coefficient, a measure if income inequality, is very high (0.38) compared to other developed countries (Central Bureau of Statistics 2011) and the country has the second highest income poverty rate (11%) in the OECD after Mexico (OECD 2011).

The usefulness of each indicator considered depends on the narrative to which it refers. A plurality of narratives results in a plurality of indicators, so that the usefulness of a representation cannot be defined in general terms. What can be observed is that the government discourse is framed around representations at a very high scale of analysis considering the ecosystems or at a very low scale of analysis considering the efficiency of water use in specific economic sectors. A technocratic approach to water management is thus privileged. Critical literature focusing on inequalities in the access to water uses yet a different scale of analysis, namely that of the individual or of society. The controversy and the fuzziness about water availability remain unsolved also because different social actors talk at cross-purposes. This is clearly shown by the multiple scales used to discuss the issue and the impossibility of evaluating the usefulness of the data produced in absolute terms.

Just like the usefulness of different representations cannot be assessed according to a general criterion, also the desirability of different policy alternatives cannot be assessed in general terms. However, the analysis of biophysical constraints makes it possible to assess the viability and feasibility of current living standards. As a result of growing water scarcity, high living standards can only be maintained through a continuous increase of imports and the specialisation of the working population in high value added activities, such as services, high-tech start-ups and so on. A large economic surplus will be needed to guarantee water provision or to externalise resource-intensive production through imports. My study shows that the current metabolic pattern of Israel is only feasible in the context of resource abundance abroad. In the context of peak oil (the maximum pace of oil supply, see chapter 2) such dependence on external inputs, and particularly on fossil fuels, may become soon highly unsustainable. The peak oil scenario threatens the very survival of socio-economic systems heavily dependent on oil imports, adding to the uncertainty of the assessment.

The problem of defining sustainability resides in the fact that changes in the identity of the system can be seen only by maintaining the same level of analysis over time, that is, the same description based on the same choice of relevant variables. As discussed by Allen and colleagues (1999) the analysis of the evolution of socio-economic systems (and more in general of autopoietic, or self-reproducing, systems) should address the unavoidable change of strategy used by the system in order to cope with changing boundary conditions.

In the first phase, when the system establishes itself, it follows a strategy of "high gain" – flows are perceived to be abundant and used to improve the stability of the identity of the system (in this example, using water to boost food self-sufficiency, increasing the population). As the system matures and becomes more complex through the creation of new activities and a more hierarchical organization of human activities, it expands in its context by using more resources. When resources become scarce, structural organisation has to adapt to resource availability. In this second phase the system has to adopt a "low gain" strategy looking for congruence between external and internal constraints (e.g. the implications of water scarcity and demographic variables) and adjust the functional and structural compartments (Allen et al. 2003).

According to this narrative the identity of Israel changed because its economy got more organised in terms of functional and structural compartments compared to its early stages. This requires that the definition of sustainability should also change along with the evolution of the system, for example from weak (there are economic substitutes for water) to strong sustainability (there is an absolute scarcity of water). Sustainability should be seen as a moving target (Holling et al. 2000).

5. Conclusions

This case study uses multiple spatial and temporal scales of analysis in order to make sense of the plurality of sustainability assessments produced about water management. Desirability is defined by looking at how social and cultural values shape the different narratives present in society and how those narratives determine the relevant attributes to be observed (what are the characteristics that matter?). The usefulness of the representation can be assessed by looking at the consistency between the narratives used and the corresponding indicators. In this sense, a large scale representation of the ecosystem is useful in the water scarcity narrative, but does not add any information to the discussion about access to water.

The question of pertinence, on the other hand, is addressed by analysing the system at different scales of analysis. Feasibility is an assessment of the compatibility of the system with the external constraints. External constraints can only be observed by adopting a larger scale of analysis (the level n+1), a scale capable of studying the processes guaranteeing the stability of ecosystems. Viability looks at the compatibility with the internal constraints, that can only be observed by adopting a smaller scale of analysis (the level n-1), where we can observe specific social structures and organisations.

Defining what is desirable entails two challenges: on one hand, the ability to deal with non-equivalent descriptive domains and, on the other hand, the unavoidable existence of non-equivalent perceptions. The use of non-equivalent descriptive domains can be dealt with through an integrated assessment (such as the one used in this chapter). Integrated assessment is defined by Rotmans and Van Asselt (1996) as the combined use different knowledge claims in order to generate a representation that cannot be derived from a single discipline.

In the case study presented, the societal metabolism view highlights the importance of the agricultural sector for the reproduction of society, the economic view reveals the role of monetary surplus in compensating the bottlenecks imposed by bio-physical constraints while the ecological view flags the growing pressure on ecosystem stability due to water extraction. Different narratives result in different choices of relevant attributes used to evaluate the sustainability of the system.

The existence of non-equivalent perceptions is captured by the analysis of different texts, official documents and publications. How to make sense of this pluralism remains an open question. In practice, the current governance of water in Israel can be seen as the unfolding of the interactions and power relations between different visions of desirability. In analytical terms, I have focused more on showing how pluralism leads to the use of multiple non-equivalent representations of the system and contradictory assessments of sustainability, rather than on explaining how these differences emerged from the specific context of the Israeli society (for the latter, the reader can refer to e.g. Shindler 2008; Shafir and Peled 2002).

In conclusion, sustainability assessments have to deal with the complexity of socio-ecological systems that can only be characterised with a high level of uncertainty and the unavoidable presence of conflicting values. Different knowledge claims have to be considered in order to check the quality of the scientific information used to inform policy, as pertinence and usefulness depend on the choice of narrative. With this goal in mind, one should avoid oversimplifications in the representation of the system and handle carefully the uncertainties faced. In the case of Israel, many different issues emerge resulting in multiple contrasting assessments of sustainability, based on the overexploitation of aquifers and of the Kinneret Lake, the goal of food self-sufficiency, the dependence on imports of fossil fuels, the growing population and income inequality, et cetera. The approach presented in this study represents a step away from reductionism in the direction of an open acknowledgment of the challenges posed by complexity. However, the question of how to handle a plurality of different value-judgements and narratives remains open.

5.2 Appendix – Data sources

The figures used for the characterisation of human activity are taken from the table K/3 “Average number of weekly work hours per employed person (incl. those temporarily absent from work), by industry” and table K/2 “Employed persons, by industry” (Central Bureau of Statistics 2010). Both tables report figures for the years 2008, 2009 and 2010. Figures for 2008 are considered.
Weekly work hours and employed persons are presented in quarterly figures, i.e. as averages of three months each. Weekly work hours vary from one quarter to the next because national holidays are taken into account. Since holidays are included in the accounting, it is considered that there are 52 work weeks per year. Employed persons vary in some industries because of seasonal work.

Yearly Human Activity (HA) of a given sector is calculated as:
HAi = 13 weeks * (weekly hours * thousand people)1st quarter + 13 weeks * (weekly hours * thousand people)2nd quarter + 13 weeks * (weekly hours * thousand people)3rd quarter + 13 weeks * (weekly hours * thousand people)4th quarter Eq. B.1

According to the compartments considered in this analysis, the sectors have been aggregated as follows:

Table 2. MuSIASEM Categories

MuSIASEM categories	National statistics categories
AG	Agriculture
PW*	Manufacturing; Electricity and Water; Construction (building, civil and engineering projects); Wholesale and retail trade, and repairs; Accommodation services and restaurants; Transport, storage and communications; Banking,

	insurance and other official institutions; Real estate, renting and business activities; Public administration; Education; Health services and welfare and social work; Community, social and personal and other services; Services for households by domestic personnel; Extra-territorial organisations and bodies; Not known

Data on water consumption is taken from table st21.05 "Water production and consumption" (Central Bureau of Statistics 2010). The table reports figures for 1969/70, 1979/80, 1990, 2000, 2006, 2007 and 2008. Figures for 2008 are considered. Figures for consumption are divided in "Agricultural", "Domestic and public" and "Industrial". In order to disaggregate water consumption of the public sector and domestic users, Table "t06 Physical flows of water corresponding to economic uses recorded in Table 2, 2006" (Central Bureau of Statistics 2010) was used as reference. Water consumption figures were classified according to the categories chosen for HA.

Data on land use for Israel is taken from table st19.2 "Agricultural crop areas" (Central Bureau of Statistics 2010). Data for 2008 is considered. Total agricultural land is calculated as the sum of the areas dedicated to the different types of plantations listed. Data on monetary flows is taken from table st18.1 "Gross Domestic Product of the business sector, by industry" and st14.2 "Gross Domestic Product and uses of resources, in the years 1995-2009" (Central Bureau of Statistics 2010). Data on food is taken from table st19.23 "Food supply balance sheet" (Central Bureau of Statistics 2010). Calories are calculated according to the conversion coefficients provided in "Food Composition Tables" (FAO 2001).

Chapter 4

Case Study: Empty promises or promising futures? The case of smart grids.[5]

1. Introduction

New and emerging technologies have long been at the centre of attention of energy policies both because of their potential benefits and because of the possible risks they pose to society. Examples are nuclear energy, fracking, agro-biofuels, to name but a few. We define emerging technologies as (1) elusive objects (Lucivero et al. 2011) with many possible functions and definitions, (2) technologies that can be applied to multiple processes and at multiple scales, (3) based on future visions, or what Jasanoff and Kim (2009) call "socio-technical imaginaries" about a desirable social order or future state of society. It follows that emerging technologies are characterised by high levels of uncertainty.

Emerging technologies are an interesting case study because representations of technological applications of those technologies are central to the science-policy interface. Scientific representations play an important role in obtaining funding for research and development of new technologies, in the debate about regulation, and in the choice of narratives. For this reason, quality assessment in this case study is applied to the representations of smart grids in relation to future visions.

Smart grids, defined as automated electric grids, are an example of emerging technologies. Smart grids are related to a plurality of different future visions such as the transition to renewable energies (Blumsack and Fernandez 2012), securing energy supply, reducing blackouts (Beyea 2010), more efficient use of resources (Wissner 2011), universal access to electricity and a decentralised system of

[5] This chapter is co-authored by Mario Giampietro.

electricity generation where producers, distributers and consumers assume new roles (Wolsink 2012). Visions of smart grids are often at odds with each other (for instance, controlling energy supply and decentralising electricity generation), due in part to the fact that the technology in Europe has not been applied beyond pilot projects at a large enough scale to be able to define precisely its function and scope of application (Giordano et al. 2012). Moreover, the various promises are based on different visions of a desired social order, including sustained green economic growth (Giordano et al. 2012) and the redefinition of social structures based on decentralisation and on the common management of renewable resources (Wolsink 2012).

How can these promises be evaluated? The goal of this case study is to disentangle the ambiguity associated with the future visions of smart grids. In order to achieve this goal, it is necessary to look more carefully at the quality of the scientific representations used to generate those promises.

In this case study, we analyse smart grids in the European context. We assess the quality of the future visions of smart grids based on two criteria: (1) the pertinence of the descriptive side is evaluated by looking at the analytical choices and at the representations of smart grids found in the literature. A multi-scale representation of the energy system is presented and the different descriptions of smart grids are mapped according to the scale of analysis they refer to. This way, the pertinence of the representation is assessed by crosschecking different problem framings; (2) the social robustness of the normative side is evaluated according to the relevance and usefulness of the narratives used by the experts to construct future visions of society. Relevance and usefulness refer to the consistency of the representation with the motivations and interests of the stakeholders and the goals of the analysis, respectively. In this case study, we were able to take into account motivations thanks to the interviews carried out with the experts. A two-day workshop was organized within the FP7 EPINET project (Integrated assessment of societal impacts of emerging science and technology from within EPIstemic NETworks), with experts and practitioners in the field of smart grids. This double check makes it possible to evaluate different narratives according to their potential application to complex energy systems.

The chapter is organised as follows. The second section outlines the methodology used to assess the representations of smart grids used in guiding policy. The third section provides an assessment of both the descriptive side, by looking at the pertinence of the representations in relation to different scales of analysis and assessing the scope of the envisioned applications of smart grids on energy systems. The fourth section provides an analysis of the normative side, focusing on the usefulness and relevance of the representations used by the experts to promote the technology. The fifth section brings together the analyses of the descriptive and the normative sides in order to give some insights about the potentials and limitations of the promises associated with smart grids. Section 6 concludes by highlighting the contribution of this case study to the development of a more systematic procedure to assess the promises of emerging technologies that is relevant to policy making under uncertainty.

2. Method

Many definitions of smart grids can be found in the literature, ranging from technical descriptions of small-scale technological applications to visions of decentralised management of common-pool resources. In this paper, we adopt the definition used by the European Commission, according to which the smart grid is a highly automated electric grid based on the use of Information and Communication Technology (ICT) (Giordano et al. 2013)[6].

[6] Note that we do not include gas in our discussion of the concept of smart grid because this paper is meant as on overview/guideline for quality assessment rather than a detailed study of smart grids. It should be noted however that gas is a primary energy source, whereas electricity is an energy carrier, so that the two discussions need to be considered separately, a point which adds to the ambiguity over smart grids.

The difficulty in defining smart grids comes from the fact that different experts attribute different purposes to this technology, and adjust the representation used accordingly. Experts focusing on consumers, tend to talk about smart meters and the associated services that can be offered to different consumer groups, and analyse the smart grid in terms of information management. On the other hand, experts arguing for a transition to renewable energies see smart grids from the point of view of energy management and deal with higher levels of analysis, acknowledging that an energy system encompasses natural resources, technology and social actors.

The literature reviewed consists of scientific articles and technical reports from smart grids pilot projects. We analyse two main narratives, which refer respectively to information management and to energy management. In the narrative defining smart grids as an information management tool, the appraisal focuses on the collection and handling of information, on the institutions regulating access to, and the use of, information, and on the stakeholders providing such information. In the narrative defining smart grids as an electricity management tool, the appraisal focuses on the set of energy transformations that make possible the distribution of electricity to final users, on efficiency in energy distribution and use, and on the types of primary energy sources used. These energy transformations are controlled by thermodynamic constraints. We define the energy system as a complex hierarchical system, that is, a system that expresses different functions at different scales of analysis due to non-linear interactions between its components.

The tension between information and thermodynamics is that the first is rate-independent and the second is rate-dependent (Allen and Hoekstra 1993). Information has no rate as it refers to the meaning of the system and it can be transferred across scales without altering the structure of the system. On the other hand, thermodynamics determines that energy is neither created nor destroyed but it can only be transformed. The rate of transformation depends on the level of organisation of the system (Allen 1987). Energy transitions are inherently long processes because they depend on changes in the organisation and structure of the system.

Uncertainty plays a very different role in the two narratives. In the case of information, the use of smart meters is seen as creating uncertainty related to privacy and data protection issues. In the case of energy management, smart grids are seen as reducing the uncertainty related to the challenge of matching electricity demand and supply in time, and of the complex transition towards renewable energy sources. The role of this emerging technology is thus seen in very different lights depending on the narrative adopted.

By analysing both the descriptive and the normative choices used to frame the debate about smart grids, one can see how the choice of representation depends on the goal of the analysis. As a consequence, the representations used to promote or cast doubt over the adoption of smart grids are an expression of the normative stand of the analyst.

The quality assessment of the promises associated with smart grids is based on the analysis of the descriptive and the normative sides, divided in two steps:

> (1) The first step consists of providing a multi-scale representation of the ensemble of natural resources, technology and human activities involved in the energy system. The representations of smart grids used for policy are allocated to the different scales of analysis identified in order to assess the pertinence of the representation, defined as the consistency between the representation and the descriptive choices.

Recalling the definition given in chapter 1, the concept of scale refers to the combination between the level of analysis (the grain and extent of the observation, such as using a telescope or a microscope) and the level of observation (the position of the observer with respect to the observed system, such as the inside view or the outside view) (Giampietro et al. 2006). The use of multiple scales makes it possible to assess the *viability* of the system (inside view looking at the compatibility of energy supply with the internal requirements of the socio-economic system) and the *feasibility* (outside view looking at the compatibility of energy demand with the availability of primary energy sources).

(2) The second step consists of assessing the social robustness of the representations and knowledge claims used by the experts and practitioners working with smart grids. Social robustness refers to the accountability and transparency of the knowledge base used for policy (Nowotny 1999). Changes in the set of transformations required to supply electricity to society, such as the decentralisation of electricity production, or the transition to renewable energies, may entail important readjustments of the socio-economic system itself, bringing up conflicting interests. In this case, the quality assessment of the representations is based on the usefulness and the relevance of the scientific information according to the social and political context.

When dealing with emerging technologies, society has very limited knowledge or experience of the new technology prior to its application, therefore the assessment of the social robustness relies on the experts. The expert workshop organised within the EPINET project included technology developers from universities, research institutions and the electricity industry; policy makers, regulators and policy advisors; representatives of NGOs and consumer organisations; consultants and entrepreneurs. A total of 9 participants took part of the workshop, 7 male and 2 female.

The participants were selected by the EPINET team based on the idea of epistemic networks (Haas 1992), defined as networks of experts using a shared set of normative beliefs, a shared understanding of causality, a set of criteria defined within the network for validating knowledge and a common claim to policy-relevant knowledge. Given this definition, epistemic networks in the case of emerging technologies can only be loosely defined. When the objects of technology assessment, in this case smart grids, are elusive, there lacks a shared set of beliefs (what is the purpose of the new technology?) and causal relations (how can that goal be reached?). Nevertheless, the practitioners interviewed did perceive each other as experts and did share the view that their competence is directed at policy. The results of the focus group are used to assess the social robustness of the normative choices.

3. Pertinence of the descriptive side

This section provides a multi-scale representation of the energy system and relates the plurality of representations found in the literature about smart grids to the multi-scale analysis. More specifically, we analyse representations related to electricity demand management, efficiency and reduction in distribution losses, the integration of renewable energies and availability of natural resources in order to check their pertinence in relation to different scales of analysis.

The term "electric grid" can have different interpretations depending on the scale of analysis, which imply considering or neglecting some of the energy transformations required to supply electricity to the final consumers. The various levels of analysis considered in this paper are illustrated in Figure 9.

We consider the electric grid as the focal level (level n). An analysis that focuses only on the characteristics of a specific set of end users representing a sub-part of the grid – for example, what is indicated as level n-1 in figure 9 – is based on a non-equivalent interpretation of the term electric grid. As an alternative, we can include in the analysis the technical processes of exploitation of primary energy sources – for example, fossil energy, wind, solar energy, hydropower – under human control required to produce electricity, illustrated as the level n+1. This inclusion changes dramatically the analysis of the performance of an electric grid.

Whereas the performance of an electric grid perceived and represented at the level n is about how to distribute a quantity of electricity already available in the most effective way, the analysis of the performance of an electric grid at the level n+1 requires a completely new set of indicators about the generation of electricity –

such as the mix of primary energy sources, the efficiency of the processes producing electricity for the different types of primary energy sources, the losses given by the distance between generation and consumption of electricity.

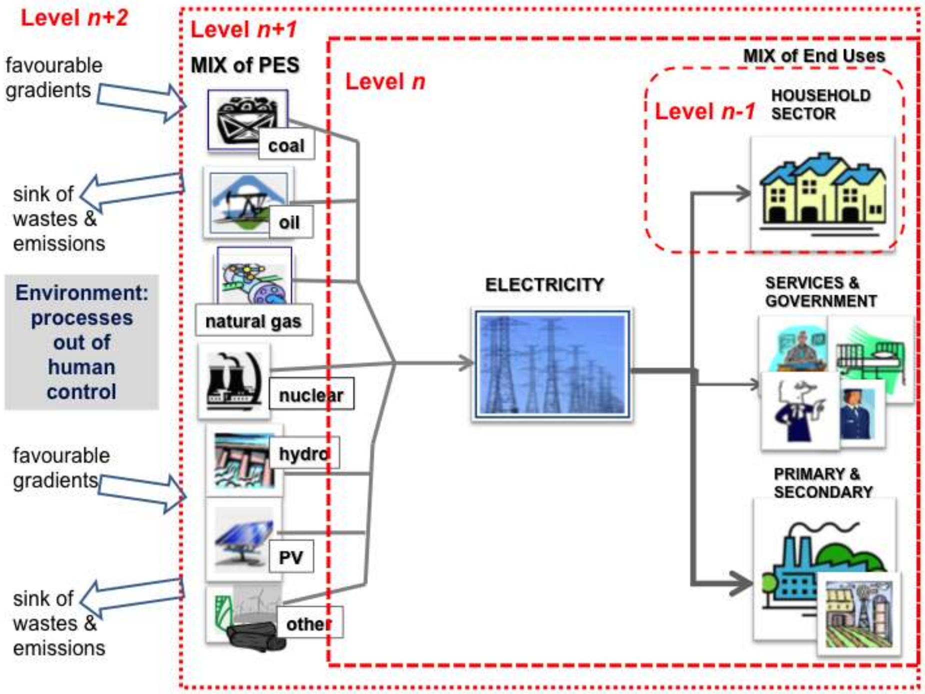

Figure 9. Different levels of analysis used to study the performance of electric grids, adapted from Giampietro et al. 2012.

Finally, since solar radiation, waterfalls, and wind cannot be produced by humans, they must be available in order to produce electricity. By moving up to level n+2, we include in the analysis also those natural processes outside human control taking place in the various ecosystems within which the societal system is embedded. At each level of analysis, we have a different characterisation of (1) the identity of the system, and of (2) the potential uses of smart grids. The ambiguity associated with the interpretation of the label electric grid implies the coexistence of non-equivalent representations (and therefore of different quantitative analyses) of the performance of smart grids.

3.1 The pertinence of the representation at Level n-1

At the level n-1, ICT can be applied to end users in order to monitor electricity consumption patterns through smart meters. The focus is on the different end users of electricity, namely households (residential consumption), the productive sectors of the economy (including agricultural sector, industry and services) and the energy sector (the internal loop accounting for the energy used to transform energy).

The evaluations of smart grids focus extensively –and often exclusively– on the privacy implications of smart meters (e.g. Hildebrandt 2013; Kostyk and Herkert 2012), an issue linked to the information narrative. Smart meters make it possible to collect information about consumption habits and estimate expected trends. This information is supposed to enable utilities to manage residential electricity demand through pricing and to raise awareness about electricity consumption in the household by sharing the information collected with the consumer. The main challenges faced in this context are the transparency in the use of data, the control and ownership of the data generated, the issue of privacy and the need for regulation on data protection.

The adjective *smart*, at this level, often refers to the use of smart meters rather than to the characteristics of the grid itself. The implementation of smart meters does not *per se* alter the electricity system, precisely because it deals with information, a rate-independent variable that does not alter the process.

In relation to the thermodynamics narrative, smart meters are supposed to help manage peak electricity demand. Smart meters collect information about consumption habits, which can be used to implement a time-of-day pricing policy making electricity cheaper at low demand times. A shift in the time of electricity consumption can be a desirable outcome of the use of smart grids, in as far as it allows shifting demand to match peak electricity production instead of increasing the power capacity of the overall system. However, it should be noted that the focus is mainly on the residential sector, which in 2012 accounted for only 30% of electricity consumption in the EU15 (Eurostat 2014a).

No studies are available to date on the potential impact of smart meters on the consumption of the secondary and tertiary sectors (the remainder 70% of electricity consumption). Smart cities projects suggest extending the application of ICT to integrate the monitoring of commercial buildings, thus potentially including the services sector in the smart grid concept. However, so far applications of smart meters are limited to the residential final electricity consumption.

Finally, smart meters are also supposed to increase awareness about electricity consumption and contribute to lowering consumption (Ambrose 2011). However, empirical studies show that the introduction of smart meters has not reduced electricity consumption, and it is reported to have led to an increase in consumption in absolute terms in some cases (Torriti 2012) or to a shift towards natural gas consumption (KEMA 2011).

3.2 The pertinence of the representation at Level n

At the level n, the electric grid includes the whole distribution system, composed of the long distance high voltage transmission system and the low voltage local distribution network. The electric grid has the function of connecting the points where electricity is produced by different types of power plants to the points where electricity is consumed by different types of users. Given the diversity of consumers and of producers of electricity, the function of smart grids is to improve the capability of matching demand with supply in real time. At this level the use of ICT does not have the goal of generating infrastructural changes in existing electricity grids. Due to the complexity of the task of matching both in time and space demand and supply of electricity, it is evident that ICT can provide a much needed help in the coordination and handling of the information required for regulating the energy conversions taking place in the electric system.

The automation of the electric grid is often linked to increased efficiency in the electricity delivery system and the reduction in distribution losses (Gellings 2009). In this case, one should not assume that increased efficiency leads to a decrease in electricity use in the long term. This is explained by the Jevons paradox, according to which an increase in efficiency in the use of energy produces temporary energy savings. The savings allow for an increase in the uses of energy, thus increasing overall consumption in the long run (Polimeni et al. 2008). The Jevons paradox can be interpreted as a heuristic tool that makes it possible to highlight the high levels of uncertainty (indeterminacy) linked to changes in complex adaptive system.

The nature of the grid itself would be challenged by the need for long-distance interconnections in the case of off-shore wind farms (Schleicher-Tappeser 2012) or in the case of long distance imports – e.g. electricity produced with solar power in the Sahara Desert and consumed in Europe, as suggested by the Desertec project (Desertec Foundation 2014). In this case, yet another dimension has to be considered, namely the costly infrastructure required to transport electricity from Northern Africa to Europe and the viability of constructing and maintaining such long-distance and international electricity networks as envisioned by Desertec. Zio and Aven (2011) also point at the increased vulnerability of highly inter-connected grids to hazards of random mechanical and material failures, natural events, intentional malevolent attacks and human errors.

3.3 The pertinence of the representation at Level n+1

At level n+1, ICT is used in order to integrate various types of primary energy sources in the existing electric power system. In this case, the scale used to look at the system is further enlarged to include the whole set of conversions associated with the primary energy sources used for electricity generation and the end uses of electricity. It should be noted that the move to this level requires a greater understanding of the complexity of the system. When considering the metabolic pattern of modern societies, the pattern of generation of energy carriers (including electricity) must be compatible with the pattern of consumption of energy carriers. This implies that the pattern of production and consumption of goods and services depends not only on economic and social factors, but also on technological and thermodynamic constraints (Giampietro et al. 2012).

An example of technological constraint is given by the fact that so far electricity has been difficult to store in large quantities over a long time. Since electricity from wind turbines and solar panels cannot be produced on demand but depends on meteorological conditions, matching demand with supply requires storage. The most advanced storage technologies that have demonstrated technical and economic viability are (i) electric vehicles batteries, which are not sufficient to provide electricity for industrial or commercial use because they function on very short time scales, and (ii) pumped-storage hydro, which depends on a favourable topography (Ekman and Jensen 2010). In this discussion, it is important to keep in mind that different forms of energy are not perfect substitutes: one cannot fly a commercial airplane on photovoltaic panels. Storage is a central issue because of the heterogeneity of functions served by different types of energy carriers.

In terms of biophysical constraints, different types of primary energy sources can be distinguished based on their different requirement of production factors (human labour, technical capital and energy carriers) per unit of net supply of energy carriers to the society. The use of primary energy sources of high quality, such as fossil fuels, makes it possible to produce a large amount of energy carriers, while using a very small fraction of human labour and energy carriers. This way, high quality primary energy sources free production factors and allow for an increase in the number of functions expressed by society (Hall and Klitgaard 2012; Pimentel 2008; Smil 2011; Giampietro et al. 2012). Conversely, renewable energies require a higher amount of energy and labour inputs per unit of electricity produced.

Renewable energies accounted for 23% of net electricity generation in the EU15 in 2012 (Eurostat 2014a). A transition to electricity produced 100% from renewable primary energy sources would thus require a major restructuring of the energy system (Smil 2006) and of the socio-economic system (Giampietro et al. 2013). Morevoer, electricity is only part of the picture in the overall energy system. Electricity consumption accounts for 22% of Final Energy Consumption in the EU15, whereas as fossil fuels (coal, petroleum products and gas) represent 67% of

Final Energy Consumption (Eurostat 2014b). That is, an economy based on green electricity, would still be far from a green economy.

In Italy, the roll out of smart meters at the national level was carried out as early as 2001 (Scott 2009), however the contribution of renewable energies to gross electricity generation stayed constant at about 20% until 2008 and increased very slowly to 28% by 2012 (Eurostat 2014a) thanks to the heavy subsidies provided by the Italian government starting from the 2007 First Energy Incentive and culminating in the 2013 Fourth Energy Incentive (ENEA 2014).

Energy transitions are inherently long processes that take decades, or generations, due to “the necessity to secure sufficient resources, to develop requisite infrastructures and to achieve competitive costs” (Smil 2011: 218). There are high levels of uncertainty related to each of the adjustments necessary. In this sense, it cannot be expected that the use of ICT will solve all problems related to the complex energy system of modern societies. Major readjustments of social structures and consumption patterns are most likely inevitable.

The viability of a transition to lower quality primary energy sources can be checked by looking at the metabolic pattern of a society using the method illustrated in figure 10 (Giampietro et al. 2013). The first quadrant relates the total population (expressed in hours of human activity) to the total energy throughput, and the third quadrant relates the human activity employed in the Energy and Mining sector to the energy throughput of that sector (the energy used to make energy). In developed societies the high quality of the primary energy sources used implies that only 0.1% of Total Human Activity is deployed in the Energy and Mining sector (quadrant 2) and only 8% of the Total Energy Throughput is used to produce the flow of energy carriers consumed by society (quadrant 4).

Due to the complex relation linking the pattern of generation of energy carriers to the pattern of consumption of energy carriers illustrated by the set of forced relations shown in figure 10, we can see that changing the overall quality of primary energy sources – for example, from a massive reliance on fossil energy to a massive reliance on renewable energies – implies changing the slope of the curve (representing the inputs required to make energy) in the fourth quadrant. This will affect the very identity of the economic process (Giampietro et al. 2012).

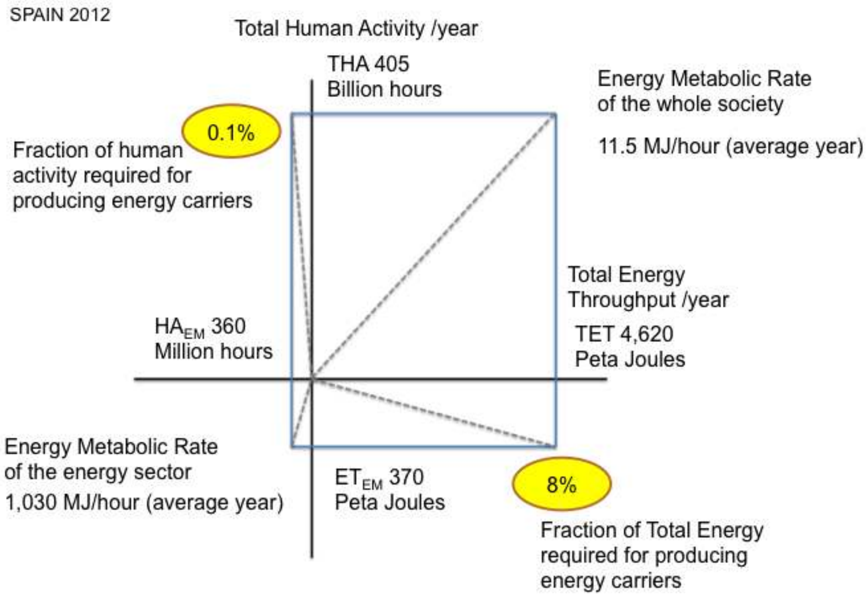

Figure 10. Multi-scale representation of the energy throughput at the level of society and at the level of the Energy and Mining sector, adapted from Giampietro et al. 2012. Data refers to Spain for the year 2012, own elaboration from Eurostat (2014a, b).

Given that renewable energies at the moment have a much lower quality than fossil energy (Hall 2011; Pimentel 2008), one should expect that a transition to an economy based on 100% green electricity would either provide a lower electricity supply, keeping the fraction of human activity and the fraction of total energy used in the energy sector constant, (case 1 in Figure 11a), or it would require a significant increase in the fraction of human activity and energy used by the energy sector, in order to maintain the current energy supply levels, and an equal decrease of energy and human activity available to the rest of society (case 2 in Figure 11b).

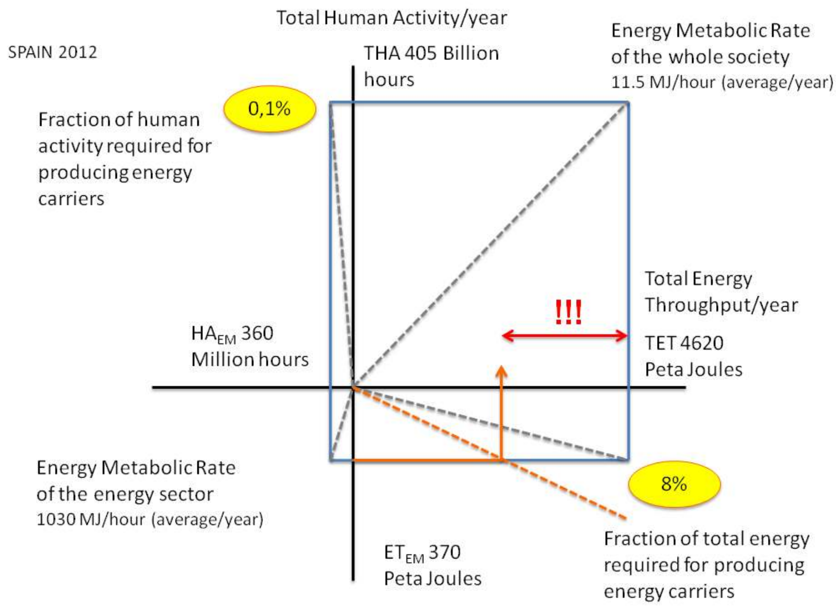

Figure 11a. Trade-offs implied by a transition to lower quality primary energy sources, energy sector.

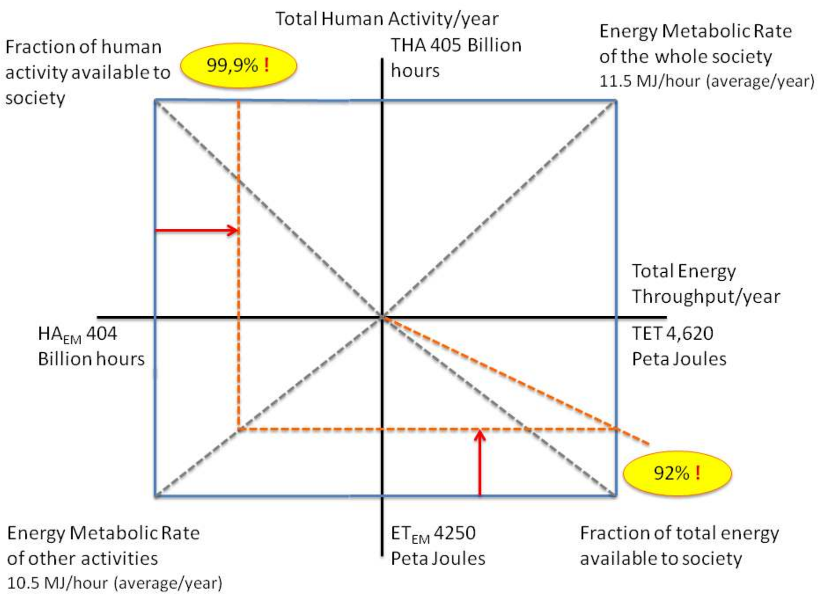

Figure 11b. Trade-offs implied by a transition to lower quality primary energy sources, rest of society.

3.4 The analysis within the narrative referring to Level n+2

At level n+2, the analysis focuses on *feasibility*, that is, the compatibility with external constraints posed by processes outside of human control, such as the natural availability of primary energy sources. At this scale, the use of ICT is irrelevant.

Topographic constraints are of utmost importance: for example, Concentrated Solar Power plants require a certain level of radiation and (Direct Normal Irradiance greater than 7.0kWh/m^2) and slope (less than 2%), making them fit only to specific areas (Giampietro et al. 2014). Wind farms require specific climatic conditions (relatively constant wind of at least 10 m/s speed) (Kaltschmitt et al. 2007). Hydropower plants depend on the availability of rivers with sufficient pressure head to activate the turbines. In all the above cases, proximity to the grid (or the cost of building and maintaining the required infrastructure) is an important factor to take into account.

It follows that a feasibility study has to be carried out for each type of alternative energy plant considered, based on the specific topographic and climatic conditions of each location considered. Given that the feasibility of alternative energies is specific to the morphology of the territory, it is hard to say that a transition is possible *in general terms* or based on average coefficients. In this case, high levels of uncertainty are associated with the availability of natural resources. The technology may be available, but alternative energy systems cannot be operated without land, rivers, solar radiation, or wind. Therefore, technological viability should not be taken as a proxy for feasibility.

4. Social robustness of the normative side

This section turns to the analysis of the normative aspects of the future visions of smart grids. In order to identify the goals and values that support different visions, we analyse the results of the EPINET workshop. The overview of the plurality of value-judgements, goals and motivations provided makes it possible to identify the visions associated with the different representations analysed in section 3.

The expert workshop carried out within the EPINET project was set up as focus group. Focus groups are a useful methodology in addressing emerging technologies (Sutton and Arnold 2013). Focus groups are a research technique aimed at data collection through group interaction, where the researcher plays an active role in creating the discussion (Morgan 1996). In our case, experts were asked to make a statement on a series of questions in a group setting and successively to respond to clarification questions by a variety of researchers belonging to the EPINET team. The workshop was articulated around three main questions, namely (1) What should a socially robust smart electric grid look like? (2) What values are served in the way the current smart electric grid(s) are being shaped? (3) What discrepancies are to be perceived between a desirable future grid and the current directions of its development?

The focused interviews in a group setting (Merton 1987) proved useful for the moderators to ask for clarifications on the experts' statements. Clarifications allowed us to identify what the informant considered to be relevant: declarations were often constructed around grand narratives ("we all want renewable energy") and the interview format proved useful in going deeper into why each informant endorses such a statement: "we need renewables because peak oil forces us to look for alternatives" is very different from "we should reduce our ecological footprint while maintaining consumption habits."

The interviews carried out during the workshop were not recorded, so that the results presented in this paper are based on notes taken by the authors during the workshop. The quotes are reported in the text using "quotation marks." The meeting was held following the Chatham House Rule, according to which neither the identity nor the affiliation of the participants may be revealed in the use of the information received. For this reason, the quotations are reported without identifying the speaker.

We present here a non-exhaustive discussion of the results, based on the selection of excerpts from the workshop notes coded in relation to (1) the usefulness of the smart grids, articulated as *promises* and *visions* of smart grids, and (2) the relevance of the technology, by focusing on the *motivations* for adopting smart grids. In terms of (3) social robustness, we considered the experts' understanding of the *role of society* at large in the development of smart grid technologies, as well as *the experts' role* in society. The codes were further analysed in terms of *coalitions* and *contradictions* that emerged among experts.

The usefulness of smart grids is assessed by looking at the definitions and envisioned purposes of the technology. There was a lot of discussion on what smart grids are. As many definitions of smart grids were provided as experts in the room, including the claim that smart grid is not a useful concept to think about the energy system so that the very term "smart grid" should be avoided. The definitions given include, among others, the "just grid," "the automation of electrical grids as a means to an end," "a tool for the transition towards renewable energies" or "towards a different societal system," "an umbrella of technical developments," "the possibility of abundance of energy to meet all our needs and reduce the ecological footprint," *et cetera*.

The variety of definitions confirms the impression that many levels of analysis are used: thanks to the fuzzy definition of the concept, smart grids include anything from distribution issues directly linked to the electric grid to the overall energy system, primary energy sources and visions of wellbeing and sustainable development, both loosely defined. The multiple definitions and visions associated with the term make the nature of the object under study unclear, generating a dangerous level of ambiguity. Benefits and risks cannot be accurately defined because of the vagueness of the definitions used.

One result of the workshop was that experts agreed on the inevitability of the adoption of smart grid technology, as exemplified by the declaration "there is no choice of whether we want it or not: the technology is here." Electric utilities are relying more and more on ICT, regardless of policy makers or researchers steering this development. Thus the question was not whether smart grids are desirable or not, but how can society benefit from their upcoming deployment. This result raises a number of questions. How do experts' opinions reflect or relate to the opinions of society? How do some technological innovations come to be adopted by default?

Relevance is assessed by looking at the motivations for adopting smart grids. Motivations varied significantly from one expert to the other. One participant argued, "The transition is not about technology but about energy sources because of the scarcity of fossil energy." On an opposite stand, another participant declared, "The goal is to have abundance of energy for all our needs and to reduce the ecological footprint." A third motivation is exemplified by the statement: "the problem is climate change: we need a complete shift to solar and wind, through IT."

A contradiction emerges in so far as smart grids are seen both as a way to change the current metabolic pattern of societies and as a way to maintain the current lifestyle (ignoring the fact that living standards depend on the current pattern of energy consumption – see Sorman and Giampietro 2013). However, there seemed to be consensus on the need to reduce the environmental impact (especially CO_2 emissions) of fossil fuels.

Social robustness was interpreted in various ways by the participants. Strong disagreement emerged in relation to the role of society. While some participants called for a democratic control of research where citizens should actively decide which direction research should take and how society should be restructured in order to adapt to different energy sources, others argued that the development of smart grids "is not a democratic process. Very few people have the competence to understand the energy system, namely engineers. The question is: what would people perceive if we gave them the right tools? Not what their values are." The latter view seemed to be more present among the experts. Another participant argued, "Consumers only care about having light when they press the switch, they do not care about how the system works." It should be noted that the quotes reported in this paper are taken out of the context of the overall debate, and the rhetorical function of some of the statements reported is lost. Nevertheless, it is possible to observe a disagreement on the roles of society and of the experts.

The disagreement about the role of the public has a long history that is common to a wide range of technologies. In the controversy over nuclear narratives, for example, there is “persistent construction of publics as technically ignorant and driven by irrational fears of the unknown” (Jasanoff and Kim 2009: 128). On one side of the debate is the idea that the public, if given enough information, will agree on the course of action decided by politicians and experts. In this case, people are assumed to act rationally, and to evaluate technology according to the single criterion of utility maximization (Wynne 1975). The opposing view is based on the consideration that in the presence of high levels of uncertainty, decision-making should take into account the plurality of worldviews found in society (Funtowicz and Ravetz 1993).

When asked to point out policy and research priorities, there emerged an overall agreement on the need for more research on public opinion given that “it is difficult to get data on energy awareness” and that “we need to eliminate the gap between participatory processes and political decisions.” The lack of data on public opinion is reflected in the fact that out of the 281 smart grid projects registered by the European Commission, only 65 (20%) engage with consumers (Giordano et al. 2013).

5. Discussion

This section brings together the descriptive and the normative sides in order to assess the quality of the representations used to inform policy. As in previous chapters, quality is assessed both according to the external criterion of consistency of the representations and to the internal criterion of fitness for purpose.

The existence of a plurality of descriptions and analyses produced on smart grids is linked to the fact that different representations portray the perspectives of different analysts. In the literature analysed and from the results of the expert workshop, we can identify the predominant use of two representations: one focusing on smart meters and privacy concerns and the other focusing on the transition to renewable energy sources.

Interestingly, the electric grid itself is not the focus of the debate. Foss Ballo (2013) argues that since the smart grid is seen as the *solution* to the problems related to electricity generation and distribution, the challenges related to the grid itself are not mentioned. As examples of policy challenges, Schleicher-Tappeser (2012) points at the political and regulatory issues implied by a potential increase the autonomy and flexibility of consumers to the top-down management of traditional power supply.

Even though they are not present in the representations of smart grids, these challenges are part of the policy debate. The challenge of regulation, the need for independent regulatory bodies and the monopolistic character of electric utilities were brought up by several of the experts that participated in the EPINET workshop as the perceived policy priorities in enabling the large-scale deployment of smart grids.

In terms of pertinence, there is an interchangeable use of different scales of analysis and narratives. Proponents of smart grids argue that the cornerstone of smart grids as a tool in the transition towards renewable energies is changing user behaviour (KEMA 2011). This argument is based on the misuse of different narratives: the focus on consumers (information at level n-1) limits the understanding of the internal constraints of the overall system (thermodynamic narrative) at the level n. The lion's share of electricity consumption is given by commercial and industrial activities, which do not respond to time-of-use pricing – an understanding gained at level n+1. Electricity generation is technically complex and not very adaptable to consumer behaviour when it comes to the analysis of the availability of primary energy sources – an understanding gained at level n+2.

In response to these issues, Schleicher-Tappeser (2012) calls for a multi-level governance of the energy system composed of both decentralised local producers, who can manage the variability of supply from renewable energy sources such as wind and photovoltaic deployed at the household level, and of the large-scale power generation required by large consumers, such as the industrial sector. In this case, it is hard to say to what extent the automation of existing electric grids can provide a solution to the challenges posed by the availability of primary energy sources outside of human control, nor to the task of restructuring complex socio-economic systems.

In terms of usefulness, we found very different results from the analysis of the literature and of the expert workshop. In the literature, there is a reduction of the plurality of value judgements found in society to a very limited number of specific issues. An example is given by the focus on privacy issues related to smart meters (information issue), which drive attention to one of the instruments (the smart meter) that are supposed to facilitate the adoption of smart grids (considered useful in relation to the thermodynamic issue). This reduces the discussion of usefulness to a single aspect and separates the assessment of pertinence, related to the thermodynamics narrative, from that of usefulness, related to privacy.

During the expert workshop, a plurality of value-judgements emerged and many contradictions were identified in relation to the motivations, goals and future visions. In this case, the usefulness of smart grids was judged in different ways by different experts. As one expert notes, “a switch to renewables requires **reducing** society’s activities: if we change the resource, we change the society” (our emphasis). In this case, shouldn’t society have a say? Wynne (1975) argues that the focus on privacy concerns is a way to point at “social facts” and thus reduces the assessment of emerging technologies to an exercise of legitimation of technological solutions to social problems.

The criteria of pertinence and usefulness seem to be independent from each other in this case study. The representation of the system at a large scale of analysis in reference to the use of renewable energies is not pertinent in relation to the discussion of the electric grid, but it is useful in order to justify the importance of the smart grid technology for society.

6. Conclusions

A myriad of promises and expectations are associated with smart grids, starting from access to electricity as a human right, the questions of justice and equality, the decentralization of the system and the changing role of consumers, all the way to sustainability issues, energy security, and climate change. In this context, it is very challenging to assess the potential of smart grids, based on the initial applications and pilot projects associated with this technology. Even more challenging is to grasp the broader social implications of the various promises of the proponents of smart grids, given that the debate at this early stage involves a limited number of social actors in the European context.

In order to deal with this impasse, we suggest a procedure composed of a quality assessment of both the descriptive and the normative sides of the visions brought forward by the experts in the field and by the literature. Bringing together the assessment of the descriptive and the normative sides, we identified the inconsistencies that emerge between the narratives used (e.g. the need to switch to a renewable energy based economy, level n+2) and the representations and policies suggested (e.g. demand-side management through smart meters, level n-1).

We argue that since the future visions of smart grids are still forming, this case study shows how emerging technologies are a battleground on which new knowledge claims are opposed to established epistemologies through the juggling of semantically open descriptive elements. Electric grids are semantically open because the term can refer to the final consumption of electricity (level n-1), to the distribution and consumption of available electricity (level n), to the generation, distribution and consumption of electricity (level n+1), or include the availability of natural processes (level n+2).

In conclusion, and in line with many of the experts we interviewed, we argue that smart grids are a means to an end, not an end in itself. However, the *end* of energy systems in Europe is not very well defined and may vary significantly depending on the political context. The integration of ICT in electric grids may or may not lead to favourable changes in terms of sustainability and social robustness depending on the goals pursued. Energy policy in the case of emerging technologies has to deal with the high levels of uncertainty that characterise the scientific information provided to policy makers.

In this context, it is important to improve the understanding of the complexity of energy systems and the societal organisation they support, and of the uncertainties related to different scales of analysis, in order to improve the pertinence of the representations used and enable an informed debate on energy issues.

Chapter 5

Conclusion

The starting point of this dissertation is the quality assessment of the science-policy interface in relation to sustainability. I have characterised sustainability science as being at the crossroads between different disciplines, generating a plurality of different representations of the same issue. The conceptual tools of complexity theory are used to analyse different worldviews, by mapping different representations on multiple scales of analysis.

Sustainability science is also characterised by high levels of uncertainty, which poses a serious challenge both in terms of (i) assessing the pertinence of the scientific information in relation to the knowledge gaps and indeterminacies of the dynamic complex systems under study; and (ii) in terms of assessing the usefulness of the scientific information in relation to the plurality of perceptions and high stakes involved in the definition of sustainability policies.

This study is directed at practitioners and scholars working on the interface between science and policy. More specifically, the focus on epistemological issues contributes to the scholarship about reflexivity. The contribution of this dissertation consists of a series of insights that address the research objective of assessing the fitness for purpose of a plurality of representations and improving the understanding of complexity and uncertainty at the science-policy interface.

1. Answering the research questions

This section explains how the research questions have been answered through the case studies. The three case studies relate to different issues surrounding the use of scientific information. In the first case study, I apply the concepts of complexity theory to gain understanding of the knowledge that informed, and led to, the crisis and I analyse the relation between knowledge and failure. In the second case study, I analyse the controversy between the plurality of political views and the plurality of scientific views in order to gain understanding of the relation between different knowledge claims. In the third case study, I analyse the relation between the promises and visions associated with the emerging technology of smart grids and the knowledge base that is supposed to back-up those promises.

The first question asked how pertinence and usefulness unfold in practice in relation to the quality assessment of the representations of complex sustainability issues. The diversity of cases analysed shed light over different configurations of pertinence and usefulness. More specifically, I found that the view of science as the best available knowledge is questioned in situations where the knowledge base is faced with failure, with a plurality of non-equivalent knowledge claims and with uncertain future visions.

The question of pertinence has to be addressed on a case by case basis. The contribution of this dissertation consists of a series of semantically open analytical tools that be tailored to the specificities of each case study and that provide both an internal (with respect to the goals of the analyst) and external (with respect to external standards or general criteria) quality assessment.

The second question addresses the poor understanding of complexity that can be found in the governance of sustainability issues characterised by high levels of uncertainty. The multi-scale approach provides a means of representing complex sustainability issues without simplifying the problem framing, the representation of the system or the sources of uncertainty relevant to policy-making. In other words, the multi-scale analysis is a representation of complexity. The new representation may not add any additional information to the plurality of representations already present in the knowledge base but it offers a way to organise and map non-equivalent representations of the same system in a coherent way. In this sense, the multi-scale approach contributes to the understanding of complexity for the governance of science-policy issues.

This approach contributes to the study of controversies, dysfunctional science-policy relations, communication breakdowns and knowledge insufficiencies by providing a means of comparing non-equivalent representations in a context of uncertainty. In this case, the assessment of pertinence does not depend on the elimination of uncertainty but on the consistency between the problem framing and the representation used. In other words, insights can be gained on the controversies analysed without producing more knowledge or deferring action until consensus is reached. This contribution is very relevant to the science-policy interface in the context of irreducible uncertainty.

2. Commonalities across case studies

This section brings together some of the common themes or patterns that emerge from the analysis of the three case studies, in order to zoom out of the specific contexts of each case and provide a general summary of the characteristics of controversial sustainability issues. I have identified four commonalities, which will be explained in turn.

2.1 The relationship between descriptive and normative choices

The case studies explore in detail the relationship between the normative and the descriptive aspects of the representation of an observed system. Hence, the first case study highlights how methodological individualism used in microeconomic analysis is based on the normative assumption that individuals are utility maximising agents, which ignores other motivations for action such as reciprocity (Polanyi 1957), solidarity (Singer 2002), the sense of belonging to a community and the affirmation of one's identity (Arendt 1958), collectivity (Oliveira 2005), human needs (Max Neef 1993), domination and common sense perceptions (Bourdieu 1990) and many *et cetera*.

In the second case study, the focus on the ecosystem scale in terms of water availability and on the technical aspects in terms of water use reveals a prioritisation of technical representations of the problem, which overlook or ignore the social and the political dimensions. The third case study is an example of how imaginaries about desirable futures (low carbon economy, increasing consumption, equity) are supported by different choices of scale of representation (the environment, the consumer, the society).

The three case studies offer a variety of examples of descriptive choices based on very different normative considerations. This dissertation is able to operationalise the claim that representations are always a selective view of the world and to provide examples of how normative choices affect representations in practice.

2.2 Silences

The exercise of comparing the normative and descriptive aspects of a representation reveals not only the relationship between these two aspects, but also sheds light over what is *not* represented. Echoing Bourdieu (1990), in science for governance, what is not said is often more important than what is said. For example, the silence over the characteristics of the electricity grid itself in the case of smart grids avoids confronting the political challenges involved in the decentralisation of electricity production, the tensions between public utilities and private monopolies, the gaps in regulation. The focus on technical aspects in water management makes it possible to avoid confronting the political and social issues of access and distribution of water. Similarly, the reduction of human behaviour to the question of utility maximisation avoids having to deal with the psychological, cognitive, social aspects as well as the complex dynamics of socio-economic systems.

2.3 Technocratic approach to uncertainty

As discussed in section 1.4, there are different approaches to uncertainty both in the production of scientific information and in policy making. Representations play a primary role in concealing and in revealing the uncertainties involved in the problem framing, in the governance of the issue and in the vulnerability to unknown unknowns. The three case studies point at one of the possible ways of working within uncertainty at the interface between policy and science. In the cases analysed, scientific information is used as a way to tame the uncertainty and the controversies that arise from it. Scientific information and technical knowledge are used as the basis for decision making, following a technocratic approach. The technocratic approach is a way of working within uncertainty by concealing the imperfections (van der Sluijs 2012).

In the case of the financial crisis, the technocratic tendency was evident in the management of the crisis in the eurozone, where the European Central Bank, the International Monetary Fund and the European Commission played a central role in imposing strict austerity measures based on economic models in Spain, Portugal, Italy, Greece and Ireland, and technocratic governments in Italy and Greece. In the case of Israel, water management is framed in terms of efficiency, technological innovations, water tariffs and of measuring the water level in the Kinneret Lake and in the aquifers. In relation to smart grids, the debate is often framed in terms of energy efficiency, technological optimism and the general public is only marginally involved in the development and testing of the technology.

2.4 Irreducible pluralism

The multi-scale approach offers some entry points for a reflexive analysis of the representations used to discuss the sustainability issues under study. One of the main conclusions reached is that controversies, communication breakdowns and knowledge insufficiencies are often linked to differences in the choice of scale of analysis, which result in contradictory or non-equivalent representations. In other words, the use of complexity theory and of conceptual tools such as scales and *holons*, results in a more complex representation of the system, which may reveal further sources of uncertainty rather than settling the controversy.

In the case of the financial crisis, pluralism can be found in the non-equivalent explanations of the crisis that emerge from different scales of analysis. As a result, there is no agreement on the causes of the crisis and on the policies that should be used to deal with it. In the case of water management in Israel, pluralism is present both in the representations and in the political interests that surround the case, contributing to the controversy over the issue. In the case of smart grids, pluralism is reflected in the myriad of promises and future visions associated with this technology, which create a high level of ambiguity over the issue.

3. Contributions of this dissertation

Zooming out further from the case studies, in this section I outline the methodological and theoretical contributions of this dissertation. The complexity theory-based approach developed in this dissertation contributes to the scholarship on the quality assessment of quantitative science used for governance by (1) offering new conceptual tools to be used in quality assessment, by (2) advancing some new arguments for the need of a reflexive governance of sustainability, and by (3) offering a different focus on contradictions, controversies and knowledge insufficiencies in the science-policy interface. I will explore these contributions in turn.

3.1 Methodological contribution

In terms of methodology, this dissertation shows how complexity theory can offer some important insights to the understanding of the interactions between different levels of analysis, feedback loops and emerging properties of the system. For this reason, complexity theory is very useful in analysing the potentials of emerging technologies, the distributional effects of natural resources management and the governance of complex systems made up of an intricate network of actors, such as the economy. However, it is important to stress that the contribution of complexity theory is not that of providing a "better" representation, but that of providing a new reading of how the plurality of non-equivalent representations of sustainability issues relate to each other. Complexity theory is used both in substantive terms for the description of the sustainability issues analysed and as a quality assessment tool to identify the pre-analytical choices associated with different descriptions.

The use of multi-scale analysis makes it possible to compare non-equivalent representations of the system. The controversies surrounding sustainability issues can be understood as differences between the points of view assumed by the observer (inside view versus outside view) and the choice of level of analysis (fine grain versus coarse grain). Knowledge insufficiencies can be interpreted as a simplification of complexity, which omits the representation of pertinent scales of analysis. Oversimplifications may lead to communication breakdowns when non-equivalent representations are used in a debate, the use of different scales of analysis means that different stakeholders talk past each other.

I argue that many controversies in sustainability science arise from differences in the focus on the *how* and on the *why* at different scales of analysis. For example, the view of smart grids as a useful means facilitating the transition towards renewable energy sources is based on the consideration of the how at a low scale of analysis (domestic consumption of electricity) confused with the why at a higher scale (scarcity of fossil fuels). The lack of consensus between economists with regards to the causes of the 2007-08 financial crisis is due to the focus on the how at the individual level (rational profit maximising agent) in the explanation of the why at the level of the economy (systemic loss of information). The lack of awareness in the use of different analytical scales poses serious problems to the pertinence of the representations used in science for governance.

Furthermore, the focus on the how, which reflects a technocratic approach to sustainability governance, overlooks important insights offered by the representations of the system produced by more long-term and holistic approaches to sustainability, such as those of theoretical ecology, bio-economics and social theories broadly defined.

3.2 Theoretical contribution

The use of multi-scale analysis in the assessment of the pertinence and usefulness of the representations used in science for governance, leads to a reflexive stance on the use of quantitative information. The simplification of scientific representations used for governance may lead to a simplified understanding of sustainability issues, which can be referred to as hypocognition (Lakoff 2010). Hypocognition is the result of applying the simplified frames used to represent complex systems to the governance of those systems.

Simplification works in a asymmetrical fashion: while it is necessary for the production of policy relevant representations of the observed system, simplified representations are not necessarily pertinent or useful in understanding the complexity and uncertainty of the system, outside of the specific policy goal for which they were created. Therefore, the use of any representation should be accompanied by the awareness of the loss of information that comes with the simplifications required to produce that representation.

Sustainability is not about easy solutions, such as using more solar panels, improving the calculation of water tables or so on. In this light, complex thinking brings awareness about the limits of sustainability science used for policy. Reflexivity in this dissertation is a call for the enhancement of modesty and a careful consideration of the role of values in science for policy (Strand and Cañellas-Boltà 2006).

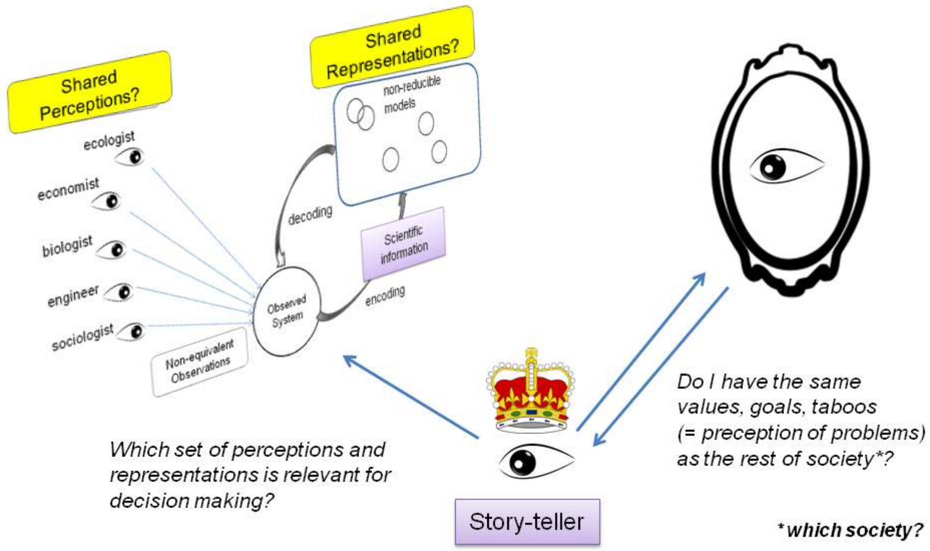

Figure 12. Reflexivity requires awareness of the values and context. Source: Kovacic and Giampietro 2015.

The definition of reflexivity used in this dissertation is in line with Varela and colleagues' (1991) discussion of self-awareness/mindfulness, that is, the ability to identify and recognise the role of values and normative beliefs (or the pre-analytical choices of a given knowledge domain) in shaping the way the observer/analyst understands and acts in the world. In other words, I relate the notion of reflexivity to the cognitive process of the observer (Varela et al. 1991) and to the social context, through an epistemic reflexivity (Bourdieu and Wacquant 1992).

In the context of science for policy, reflexivity requires asking: How do the observer's values, goals, taboos relate to the rest of society? Which society is taken as reference? Reflexivity is represented in Figure 12 according to the theoretical framework used in this dissertation. In relation to sustainability, Allen and colleagues express this set of questions as: "Sustainability of what, for whom, for how long, and at what cost?" (Allen et al. 2003: 26).

This dissertation contributes to what Voss and colleagues (2006) refer to as first-order reflexivity, that is, a reflection on the scientific information used for policy. Second-order reflexivity refers to the impact of reflexivity in changing the way in which science and policy relate to each other.

First-order reflexivity is achieved by basing the quality assessment on the notion of (i) usefulness, which makes it possible to adapt the definition of quality to the purpose of each case study and thus to work within pluralism and complexity; and of (ii) pertinence, which makes it possible to assess the quality of scientific information based on an external referent and to compare different case studies. The combination of these two criteria provides a powerful tool to avoid reductionist accounts of the challenges faced by the interface between science and policy.

The approach developed can also contribute to the study of controversies. Boltanski and Thevenot (1991) distinguish between "relativism," the definition of what is important in a specific context, and "relativisation," the claim that no agreement can be reached because everything depends on circumstances. The focus on pre-analytical choices serves precisely the goal of defining the context for debate, without falling into relativisation. In other words, relativism makes it possible to contextualise and assess the usefulness of non-equivalent descriptions of the observed system. I argue that relativism, defined as awareness to context, constitutes an important quality check in applied science.

4. Limitations

The case studies have contributed both to answer the research questions and to a wider discussion on methodological and theoretical contributions. Nevertheless, the theoretical framework used and the methodological choices present some shortcomings, which should be made clear.

The normative aspects identified in the case studies should not be understood as the identification of the values and beliefs of the observer, but as a reflection on how values and beliefs condition the choice of scale of analysis. In other words, the statements and interviews analysed in the case studies referring to water management in Israel and to smart grids are taken at face value in order to highlight the analytical implications of the representations they refer to. The rhetorical character of certain statements (such as, “everybody agrees on what our aim is”) is not considered and neither is the social and political context from which they are taken.

The methodology developed in this dissertation is based on disciplines (Rosen’s modelling relation and semiotics) that focus on the cognitive process in very general terms, and are inadequate to the study of the interaction between individuals and the social context. An analysis of the contexts in which the statements analysed are pronounced, or a discourse analysis that takes into account power relations, are out of the scope of this dissertation in relation to the methodology deployed. Nevertheless, since the conclusions of this dissertation point towards the importance of reflexivity, the social context is an important aspect to be considered. The analysis carried out in the case studies can be thus considered as complementary to approaches such as ethics studies, environmental sociology and discourse analysis.

A second limitation of this dissertation resides in the fact that the concept of reflexivity is used as a basis for reflections on the challenges of the science-policy interface and on the handling of uncertainty, but no indications are offered for an operational use of the insights provided. As a consequence, it is important to stress that reflexivity should not be seen as an easy fix to solve controversies or to guide policy. The conclusions reached in this dissertation are more of a theoretical contribution to the understanding of the challenges involved in the used of science for governance, than a set of practical recommendations. The practice of reflexivity is not something that can be easily implemented or that has an established procedure. Much like complexity, reflexivity requires craft skills and experience. As Bourdieu (1990) suggests, reflexive approaches are not necessarily useful for action but can rather be seen as an analytical tool used to problematize issues otherwise seen as natural or inevitable.

A third limitation resides in the applicability of the approach developed. The multi-scale analysis is a pertinent tool when it comes to analysing cross cutting issues that can be represented from a variety of different disciplines and scales, as a way to make sense of controversies and knowledge insufficiencies in applied science. However, this approach is less suitable to the assessment of theoretical controversies within science or of political controversies. In other words, the approach used has been tailored to the object of study, namely the interface between sustainability science and policy, and is not so useful to the study of, for instance, controversies over which disease should be given priority in health policies, over privacy and data protection, or over human rights. In other words, the contribution of this dissertation is limited to epistemic quality assessment of complex sustainability issues, and does not refer to substantial or procedural quality assessment.

5. Future developments

Further research on the use of complexity theory-based tools for quality assessment is required in order to test the potential of this approach in practice, in improving the dialogue between science and policy. The controversies that arise from different representations of complex sustainability issues can be understood as different approaches to uncertainty, and as a consequence these controversies do not find a solution in the production of more scientific information when faced with irreducible uncertainty. Complexity theory offers a way to cope with uncertainty, instead of reducing it. In this sense, one potential line of future research consists in the application of the analytical tools offered by complexity theory in guiding policy towards reflexive governance. The complexity approach can provide interesting applications in advising policy to work within imperfections by focusing on the handling of uncertainty in the process of decision making rather than trying to eliminate or ignore it. The ultimate goal should be that of reflexive governance obtained by flexible institutional arrangements and strategies based on the awareness of the limitations of scientific information.

In so far as complexity theory offers a way of dealing with pluralism, it is also an interesting tool for the study of the science-society interface. This application opens the way to the assessment of the societal dimension of uncertainty and to a broader assessment of controversies. As a future line of research, it would be interesting to test the potential of using the conceptual tools of complexity theory, including multi-scale representations of specific issues, as a support tool for structuring debates in participatory processes.

The advantage of using multiple scales of analysis is that diverging points of view do not need to be directly compared or measured against each other but can still be visualised in the same option space, and be part of the debate. More research is needed in order to check whether the use of complexity theory can help move away from relativism as an excuse for inaction towards pluralism as a basis for policy. The extent to which such a tool can be used remains to be tested. Given that multi-scale representations, as they have been used in this dissertation, do not address underlying normative debates, the contribution of complex representations for structuring debates would consist more of raising awareness or broadening the dialogue, rather than of supporting deliberation or consensus.

Another line of future research regards the potential contribution of multi-scale quality assessment to interdisciplinarity and the possibility of integrating the approach developed with other methodologies. Calls for interdisciplinary approaches are based on the view that different disciplines are complementary, yet the practice of interdisciplinarity is often an elusive goal (Blanchard and Vanderlinden 2010). This dissertation takes a more critical view of the potential for complementarities between different disciplines and shows that different descriptive and normative choices result in non-equivalent representations. The implication is not necessarily that different disciplines can be integrated, but rather that different disciplines describe different aspects of the same system. Acknowledging this incommensurability can be seen as way of redefining interdisciplinarity as a strategy used to obtain an overview of the plurality of representations that need to be taken into account.

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Appendix 1

List of Publications

Kovacic, Z. and Giampietro, M. 2015. Beyond "beyond GDP indicators:" The need for reflexivity in science for governance. *Ecological Complexity,* 21: 53-61.

Diaz-Maurin, F. and **Kovacic, Z.** 2015. The unresolved controversy over nuclear power: a new approach from complexity theory. *Global Environmental Change,* (in press).

Kovacic, Z. 2014. Assessing sustainability: The societal metabolism of water in Israel. *International Journal of Performability Engineering,* 10 (4): 387-399.

Kovacic, Z. and Ramos-Martín J. 2014. Accounting for human activity and socio-economic characteristics. In: Giampietro, M., Aspinall, R.J., Ramos-Martin, J. and Bukkens, S.G.F. (Editors) *Resource Accounting for Sustainability Assessment: The nexus between energy, food, water and land use.* Routledge.

Serrano-Tovar, T., Cadillo Benalcazar, J., Diaz-Maurin, F., **Kovacic, Z.**, Madrid, C., Giampietro, M., Aspinall, R.J. and Bukkens, S.G.F. 2014. The Republic of Mauritius. In: Giampietro, M., Aspinall, R.J., Ramos-Martin, J. and Bukkens, S.G.F. (Editors) *Resource Accounting for Sustainability Assessment: The nexus between energy, food, water and land use.* Routledge.

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S.G.F. (Editors) *Resource Accounting for Sustainability Assessment: The nexus between energy, food, water and land use.* Routledge.

Diaz-Maurin, F., Cadillo Benalcazar, J., **Kovacic, Z.**, Madrid, C., Serrano-Tovar, T., Giampietro, M., Aspinall, R.J. and Bukkens, S.G.F. 2014. The Republic of South Africa. In: Giampietro, M., Aspinall, R.J., Ramos-Martin, J. and Bukkens, S.G.F. (Editors) *Resource Accounting for Sustainability Assessment: The nexus between energy, food, water and land use.* Routledge.

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Afterword

The last three years have truly been a process of evolution for me, both on a professional and on a personal level. I have had the opportunity of meeting and working with so many interesting and inspiring people, of learning and developing my own thought, of finding myself in what I like to do and in the choices that have brought me here.

I started my Ph.D. in December 2011, at the height of the economic crisis in Spain and just after the institution of a technocratic government in Italy, and quite engaged in these events I started working on what would become my first paper right away. This way, I worked through many of the concepts of complexity theory by applying them to what I was most familiar with, economic theory.

During my second year, I got involved in the GIZ-funded FAO project "Application of the MuSIASEM approach to three cases in the agri-food sector (MUSIASEM)" (GCP/GLO/445/GER (GIZ)), in collaboration with the Energy Team of the Climate, Energy and Tenure Division (NRC) of the UN Food and Agriculture Organisation (FAO). The project consisted of the application of the MuSIASEM approach to the nexus between energy, food, land use and water for three case studies.

Due to the highly interdisciplinary nature of the project, our research group worked as a team in an attempt to bring together different types of expertise under the same problem framing. This proved to be a very challenging task, both from an epistemological point of view and in terms of managing different people, different ways of working and of communicating. The project was a very instructive experience for me in thinking about the challenges of interdisciplinarity. I later on applied the nexus approach to the case study of Israel, with a focus on water.

I have been involved in the EU funded project EPINET – "Integrated Assessment of Societal Impacts of Emerging Science and Technology from within Epistemic Networks". The EPINET project was aimed at the integration of a variety of methods of technology assessment, which presents important epistemological challenges. This project has given me the opportunity to further develop my understanding of science-policy issues, with a particular focus on emerging technologies. My third case study was elaborated within this project.

My dissertation is thus the result of both theoretical investigations and personal experiences. Throughout this process, I have deepened my understanding of the issues I was studying and my awareness of my own limitations.

Finally, the research stays that I had the opportunity to do have greatly enriched this experience. I spent two months at the Federal University of Rio de Janeiro, Brazil, where I collaborated in the preparation and teaching of a course on MuSIASEM – an excellent test of my own knowledge and understanding. During the last year of my Ph.D., I have spent three months at the Centre for the Study of the Sciences and the Humanities (SVT), at the University of Bergen, Norway. The latter stay has been of fundamental importance for me to find my positioning in the academic community in which I am entering.