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The unresolved controversy over nuclear power: A new approach from complexity theory

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ABSTRACT

We explore the controversy over nuclear power by looking at the plurality of *narratives* that have emerged throughout its history. We find a lack of consistency between the visions of nuclear power put forward by governments and industry and the experience associated with economic viability, nuclear accidents, waste handling, and so on. We use the conceptual tool of *holon* from complexity theory to provide a link between the models used for the governance of nuclear power and the realization of those models. The analysis of the holon over time reveals a systemic inconsistency between the way in which the story about nuclear energy is told and the experience gained after implementing nuclear energy according to the story. This inconsistency is due to the incompatible levels of observation used by different social actors endorsing different perspectives. The implementation of nuclear power has been based on the engineering view, focusing on the functioning of the nuclear power plant considered in abstraction from the wider implications of the adoption of this technology on the environment, on the economy, and on society. We cross-check this narrative with the societal metabolism view in order to provide a long term perspective of the interdependencies between nuclear power and the complex socio-economic system in which it is embedded. We conclude that the controversy over nuclear power may be treated as a problem of contrasting beliefs and normative values in clear disjunction from experience. The analysis presented in this paper suggests that more attention should be given to the quality of the narratives used in policy making.

1. Introduction

Nuclear power is a hugely controversial technology affected by systemic problems for which no solution is realistically envisioned in the foreseeable future (Diaz-Maurin, 2014). Yet, nuclear energy is part of the energy mix and very present in the everyday life of some Western countries (e.g. France, United Kingdom, United States). Recently a number of developing countries like China, India, Brazil and South Africa are also starting to deploy nuclear power (e.g. SA DOE, 2011; Ramana, 2012; Mathai, 2013; Diaz-Maurin, 2013). This is occurring in spite of evident doubts over its desirability, following the prominent role of nuclear energy in World War II and some of the worst industrial disasters ever experienced worldwide (e.g. Bradford, 2012). No other man-made technology has been as controversial and, at the same time, as largely deployed as nuclear power over the past 60 years.

This paper explores the controversies over nuclear power, a critical aspect to be addressed in the governance of energy technologies and especially in discussions over the desirability of alternative energy sources. The focus will largely remain on the United States, the first country to develop this technology.

Section 2 provides an overview of the history of nuclear power in the United States (US from now on in the text). This section identifies the main actors, how their various perceptions about nuclear power have been formed and maintained, and how they have influenced the development of the nuclear power industry. The section also introduces the plurality of narratives used in the debate about nuclear power. In this case, narratives are understood as stories about causality that give commensurate experience to a plurality of perceptions of a given system. Narratives are the central focus of this paper because they reveal both the differences in perceptions, which sustain the controversy over nuclear power, and the inconsistencies in the representations of the system used for guiding policy and showing limited responsiveness to negative feedbacks such as nuclear accidents.

Using insights from complexity theory, Section 3 introduces the concept of *holon*, an analytical tool used to simultaneously

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consider the external and the internal views of a system (Koestler, 1968), in order to establish a link between a given realization and the meaning given to that realization. Applied to the field of energetics, the concept of holon is useful to provide, and relate, the thermodynamic (the technical description) *and* the semantic (the function and meaning) readings of energy systems. This section explains in more detail the importance and role of narratives in the production and use of scientific representations for governance.

Section 4 applies the theoretical concepts presented in Section 3 in order to revisit the history of nuclear power in the US presented in Section 2. It provides an analytical tool we call "Dominant Narrative Analysis" (DNA) of the nuclear energy system. The DNA goes beyond the historical analysis and makes it possible to track hegemonic actors and their narratives, as well as the subsequent realization of the system over time. The DNA highlights the discrepancies in time frames used in the realization of the holon.

Section 5 discusses how the DNA of nuclear power in the US sheds light on the systemic controversy of this technology by revealing the disconnection between beliefs created on paper and experience made on the ground.

2. Historical analysis of nuclear power in the United States (1939–2013)

This section provides a historical overview of the large-scale deployment of nuclear power in the US divided into six phases: (i) a first period of exclusive military applications (1939–1945); (ii) a period of initial optimism over possible civilian applications (1946–1953); (iii) the creation of the nuclear industry (1954–1974); (iv) a halt in nuclear plants construction and public support (1975–2001); (v) a second period of optimism over a possible "nuclear renaissance" (2001–2011); and finally (vi) a second period of "slow down" following the reactor accidents at Fukushima (since 2011).

The narratives discussed in this section emerged from the following actors: (a) governments, (b) private electric utilities and reactor vendors (making up the nuclear industry), as well as (c) activist groups from the general public (Rosa and Rice, 2004). The selection of actors was based identifying the main controversies surrounding nuclear energy, and how they developed over time, rather than on a sociological analysis of the stakeholders involved. The drawback of this choice is that actors and their perceptions throughout the history of nuclear power are not contextualized, but it serves the purpose of identifying controversies.

For each phase, we identify the main narratives used in the debate about nuclear energy. The narratives reported are a selection of statements taken from policy documents, speeches from government officials, public opinion polls and corporate documents. These narratives were selected with the goal of providing an overview of the broad span of opinions and perspectives about nuclear power, rather than a comprehensive account of all possible narratives. This choice is motivated by the fact that the analysis is focused on the controversies over nuclear power, rather than on the representativeness or popularity of different claims.

A detailed analysis of the history of nuclear power is provided as supplementary material.

2.1. Period of exclusive military applications (1939–1945)

The first phase corresponds to the use of nuclear fission discovered in the late 1930s (Bohr and Wheeler, 1939) for military purposes during World War II. At that time, there was a race for the domination of nuclear fission reaction across the Atlantic Ocean with fears from scientists that Germany would develop a nuclear bomb (Einstein and Szilárd, 1939; CNRS, 1939). In the US, a nuclear program almost exclusively oriented toward military purposes was therefore developed under the control of the government (Duffy, 2004)—the only actor at the time. This period of exclusive military applications of nuclear energy was epitomized by the Manhattan project in charge of the development of the first atomic bomb between 1942 and 1945, leading to the first atomic bombings on Hiroshima and Nagasaki in Japan in August 1945.

2.2. Period of initial optimism (1946–1953)

Nuclear energy was still perceived by governments as being of national interest (Duffy, 2004). In particular, the US Government emphasized the need for keeping the technological leadership over the use of nuclear energy for military purposes (making bombs and powering submarines) and the development of the first civilian applications (reactors for making electricity) although with no public consultation (Duffy, 2004).

In order to attract private investments, the government had no choice but to release information on the current developments of this technology that had been kept secret so far (Duffy, 2004), as enacted by the first Atomic Energy Act of 1946. The resulting consensus over the use of nuclear energy for civilian applications was made possible by the fact that it was exclusively the supporters of such a program (nuclear scientists and some politicians) that were aware of its existence, and thus were the ones involved in consequent political action (Duffy, 2004).

At the same time, political and technical difficulties explain a lack of investor interest; perceptions were preoccupied with an uncertain return on investment of nuclear plants reinforced by its long time span (Duffy, 2004). In such context, the creation of a civilian nuclear industry seemed impossible without the government's financial support.

In order to bring the debate to the public sphere, governments had first to change the collective imaginary about the nuclear bomb. In this context, US President Eisenhower's 1953 speech to the United Nations introduced the distinction between "atoms for war" and "atoms for peace" (Gamson and Modigliani, 1989). The US Government therefore played an important role both as promoter of the new technology and as its regulator (Rosa and Rice, 2004).

2.3. Creation of the nuclear industry (1954–1974)

In order to further encourage private companies to invest in nuclear power, in 1954 the US approved an amendment to the Atomic Energy Act of 1946, effectively creating a civilian nuclear industry. This law implemented an all-out support deployment plan consisting of subsidies and other financial incentives given to private companies along with the necessary technical information that had, up until this point, been restricted to government use. Under the Atomic Energy Act of 1954, reactor vendors were created and electric utilities were able to enter the market on "turnkey" contract bases (Duffy, 2004), with no additional cost other than switching on the reactor (Rosa and Rice, 2004). The plan was greeted with great enthusiasm by private companies. This was epitomized in 1954 by Lewis L. Strauss, a former businessman who had recently been appointed as Chairman of the US Atomic Energy Commission (the forerunner of the US Nuclear Regulatory Commission and the US Department of Energy nuclear program), in a speech to the National Association of Science Writers: "Our children will enjoy in their homes electrical energy too cheap to meter" (1954). Nuclear power was even considered as a possible substitute to fossil fuels making possible for human societies to live in a "post-scarcity" world (Hubbert, 1956), with some anticipating a "nuclear revolution" (Time Magazine, 6 February 1956).

A critical moment came in late 1963 when Jersey Central Power and Light—an electric utility—and General Electric—a reactor vendor—signed a contract to build a nuclear power plant in Oyster Creek, New Jersey. This plant would become the first power plant to be built without federal subsidies in direct competition between vendors (US DOE, 2013) indicating to their competitors that nuclear power had become an economically viable alternative for generating electricity. The last deadlock preventing the creation of the nuclear industry was thus broken leading to a period of rapid expansion termed "great bandwagon market" (Bupp and Derian, 1978; Duffy, 2004). Between 1963 and 1967, American utilities ordered the building of 70 reactors, with about 80% of these orders being placed in 1966 and 1967.

Concerns began to surface in public opinion on nuclear affairs in the mid-1960s as reactors were being built all around the country without public consultations (Duffy, 2004). The concerns emanating from this governance issue were greatly influenced by the coincidental birth of environmental and conservationist movements. Logically then, public concerns first focused on environmental and safety aspects. However, such concerns were ignored by the government and private investors as the first oil crisis was looming.

The 1973 oil crisis revived economic concerns over the competitiveness of nuclear power plants. First, the oil crisis suggested to some that electricity—mainly coal and nuclear power—was the only alternative to oil (Yang, 2009). In addition, critics pointed to the apparent failure of nuclear power to establish decisive economic superiority over coal in spite of a quadrupling of fossil fuel prices (Bupp and Derian, 1978). The peak in oil prices convinced many that nuclear power was not a competitive energy source, as it did not reduce dependency on fossil fuels imports (Bupp and Derian, 1978). The period of fast expansion of the nuclear industry ended with harsh debates over the economic viability of nuclear power (Bupp and Derian, 1978; Duffy, 2004). The counterintuitive dependence of nuclear power on oil consumption suggested by this period was evidenced only later (van Leeuwen, 1985; Coderch Collell, 2009; Diaz-Maurin and Giampietro, 2013a; Shakouri et al., 2014).

2.4. Halt in nuclear plants construction (1975–2001)

After the oil crisis of the mid-1970s nuclear optimism came to a halt, illustrated by a wave of cancelations of orders of new reactors (Bodansky, 2004). The expected reduction in the cost of building reactors never happened (Bupp and Derian, 1978; Grubler, 2010). In the US this resulted in a halting of commissioning and building of new plants until the end of the 1990s. In France—one of the very few countries where the deployment of nuclear power was sustained throughout the period—construction and operating costs of nuclear reactors have followed a negative learning curve (Grubler, 2010), confirming the existence of a systemic problem of economic competitiveness of nuclear power (Duffy, 2004; Bradford, 2012, 2013). The *belief* in the promises of nuclear energy as a substitute for oil had already dissolved (Bupp and Derian, 1978; Yang, 2009; Smil, 2010a) as concerns over the risks involved by commercial nuclear reactors were rising.

Public opinion went from expressing concern to opposing nuclear power due to the growing concerns over the effects of radiation on health and the environment although the core reason for opposition still related primarily to the governance of this technology (Slovic, 1987; a review in Chap. 2 of Diaz-Maurin, 2013). The release of the film *The China Syndrome* on March 16, 1979—twelve days before the Three Mile Island nuclear accident—suggests that nuclear power became a growing concern of public opinion *before* the world ever experienced any commercial reactor accident (e.g. Otway et al., 1978). The Chernobyl accident of 1986 in Ukraine confirmed the public's skepticism about nuclear power (Rosa and Dunlap, 1994). The first two commercial reactor accidents of Three Mile Island and Chernobyl irreversibly crippled the nuclear industry in the US (Pidgeon and Demski, 2012), although opinions worldwide were not dramatically affected in the direct aftermath of these accidents (Gamson and Modigliani, 1989).

Given the turn toward safety in the dominant perception in public opinion (e.g. Slovic et al., 1980), the nuclear industry claimed that the lessons from those accidents were learned and that new advanced reactors addressing those safety problems would soon be available, even providing hope for a second nuclear era (Weinberg and Spiewak, 1984; Weinberg et al., 1985; Forsberg and Weinberg, 1990). However, risk experts themselves acknowledged that the learning process of such a complex technology implies inherent safety problems (Weinberg, 1994) with unavoidable or "normal" accidents (Perrow, 1984).

2.5. Second period of optimism called "nuclear renaissance" (2001–2011)

The turn of the millennium sees willingness from the US Government to engage in a "nuclear renaissance" (US DOE, 2001; Grimston and Beck, 2002; Nuttall, 2004). Prospects of new deployment of nuclear power were articulated around two arguments: energy security and climate change mitigation. On the one hand, in a context of limited resources, ensuring energy supply goes from being a national priority (limiting the dependence on imports of oil) to a global issue (the need for alternative energy sources to face peak oil). On the other hand, environmental concerns were brought forward in order to reinforce the argument that nuclear power can help reduce CO_2 emissions and alleviate global warming. Nuclear power has been widely described as a "low-carbon" or even "carbon-free" and "renewable" energy source (e.g. Deutch et al., 2003; Deutch and Moniz, 2006; *The Economist*, 17 March 2011; WNA, 2013).

New concerns emerged regarding the governance of nuclear power, which supposedly required abrogating decision power to an elite of experts and technocrats (Gamson and Modigliani, 1989; Suzuki, 2011; Funabashi and Kitazawa, 2012; *Nature Editorial*, 16 August 2012). The lock-in created by nuclear power is therefore not just technological but also institutional. Public accountability was evoked as a way to mitigate this problem. Although public opinion in most countries engaged in an important nuclear program was slowly showing an increasing acceptance of a "nuclear renaissance" (Pidgeon et al., 2008), there lacked the economic means to deploy further nuclear power, especially as the costs of designing and building new reactors continued to increase (Cooper, 2010).

In parallel, new problems came into the picture: the issue of nuclear waste disposal acquired prominence as well as the perceived risk of terrorism after the 9/11 attacks in the US. The US Government was forced to provide financial support to its (re)deployment plan. A new federal Energy Policy Act passed in 2005 that proposed tax incentives and loan guarantees to private investors for building new reactors. However, this second period of optimism turned out to be a marketing strategy unable to pass economic muster (Bradford, 2010; Nelson, 2010).

2.6. Second period of slow down (since 2011)

After the nuclear accidents at Fukushima, Japan, following the Tohoku-Kanto earthquake and tsunami that occurred on 11 March 2011 (Schneider and Froggatt, 2012), all the systemic problems of nuclear power seemed to resurface at once: reactor vendors did not find a way to lower costs, worsened by the new safety measures required for reactors, leading to cancelations and delays of new reactors (e.g. Sovacool, 2011; Shrader-Frechette, 2011; Bradford, 2013; Digges, 2014; Lévêque, 2014); governments did not defined a political and technical strategy to deal with the problem of nuclear waste and to effectively manage unavoidable accidents (e.g. Takubo, 2011; Perrow, 2011); public opinion remained generally opposed to further expansion of nuclear power (e.g. Ramana, 2011; Pidgeon and Demski, 2012) although with some exceptions like in the United Kingdom where no marked changes in public concern were observed since 2011 (Poortinga et al., 2013).

Nuclear power went from being seen by the public as "not part of the solution" (Ferguson, 2007) to being seen as "part of the problem" after the accidents at Fukushima (Costanza et al., 2011; Gropp, 2012). In the post-Fukushima era, nuclear power finds itself in a delicate situation where its systemic problems affect each other. For instance, problems of safety affect costs—there is a "cost escalation" due to new safety requirements against risk from terrorism and from tsunami-earthquake failure modes (Nöggerath et al., 2011; Bradford, 2012; Lévêque, 2014)—and vice versa—the increasing capitalization of the nuclear power-supply system affects its ability to remain flexible, i.e. its ability to integrate changes to the safety design of new reactors and new safety features to existing reactors according to its so-called learning process. The nuclear industry seems locked into a process of self-destruction exemplified by the cost overruns and delays for the construction of new reactors in France and Finland (Schneider and Froggatt, 2012) and the problem of delivering new safety design licenses in the US (Bradford, 2013).

3. Using semiotics and complexity theory to revisit the history of nuclear power

The controversy over nuclear power seems to persist notwithstanding recurring problems and accidents. We argue that one possible explanation of this controversy lies in the irresponsiveness of the models used for the governance of this technology. This section explains the relationships between perception and representation and how they serve in the creation of narratives and in the process of modeling. Building upon insights from the fields of semiotics and complexity theory, we highlight the importance and the role of narratives in the governance of nuclear power. First, the description of the modeling process is useful to describe the process of creation of meaning by relating one's understanding of the world to their experience. Second, complexity theory is useful to describe the multiple scales of analysis that can be used to represent a system, as in the case of nuclear power. Such a conceptual framework makes it possible to illustrate the set of necessary abstractions needed to construct formal models about the world, and explain how abstract models—such as the ones used by engineers in the construction of nuclear power plants—may be disconnected from experience, as we will show for the case under study. Hence, the controversy over nuclear power is interpreted as a series of mismatches between non-equivalent representations of the system and experience.

3.1. Narratives, models and the semiotic process

In the case of nuclear power, we argue that there is a mismatch between experience (the realization of a system) and perception (the meaning the story-teller assigns to such experience). This mismatch is due to the fact that the models used to represent the nuclear power system are not validated by experience, but result from a series of abstractions derived from perception. From the point of view of semiotics—the study of the meaning assigned to signs and symbols, and of sign processes (e.g. Eco, 1976)—models can be defined as formal representations of the external world, being mental, on paper or computer-based, depending on the observer's perception. Perception, in turn, is related to the narratives chosen by the story-teller, that is, stories about causality that ground and legitimize knowledge and practices (Lyotard, 1984). The story-teller and the observer refer to the two possible roles played by the analyst (one single physical entity) in relation to a system: the analyst can act as an observer—deciding on the representation—or as a story-teller—deciding on the perception. The distinction between the two roles of observer and story-teller has important implications as it maintains the distinction between, respectively, representation and perception of the system.

In order to discuss the relationship between representation and perception of systems, Rosen (1985, 2000) proposed a general theory of modeling that describes the process of production of a model as composed of four steps (Fig. 1). First, the analyst makes the pre-analytical choices of what to observe depending on their perception of the external world (causal relation). The observed system is defined as distinct from its context according to the choice of a finite set of relevant attributes associated with the system that reflects the goals and beliefs of the story-teller. For instance, the identity of a "dog" as a relevant unit of observation separate from the context of "mammals" is not an intrinsic property of dogs, but a decision of the story-teller (Giampietro et al., 2006). This first step is at the core of Rosen's modeling relation.

Second, the analyst proceeds to the encoding of the relevant attributes of the observed system into a set of measurable variables. The process of encoding requires the selection of a type to which the observed systems belong (Mayumi and Giampietro, 2006). An example might be the selection of a specific type of dog (e.g. a German shepherd). Through encoding, the story-teller gives meaning and delimits the observed system to be studied.

Third, the analyst constructs the formal system, that is, the model representing the observed system. The construction of a model allows for predictions to be made about the behavior of the observed system. For instance, once the relevant variables are isolated, the formal representation of the system "dog" can be used to infer the speed of different observed types based on the measurement scheme adopted. The model is thus a formalization of the narrative, in as far as expected causality is used to make inferences about the observed attributes of the system.

Last, the analyst can proceed to the decoding of the predictions about the observed system made through the model. Decoding links the model to the experience of the observed system. This last step makes it possible to check the consistency between the model

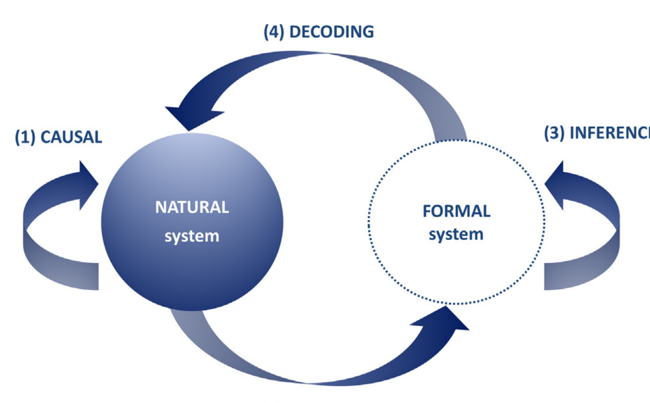

Fig. 1. General theory of Rosen's modeling used in the semiotic process of complex systems (after Rosen, 1985, 2000).

and experience. If the predictions are consistent with the observed behavior of the observed system, the model is said to reach "semantic closure" (Pattee, 1972). Semantic closure, in other words, ensures the consistency between the pre-analytical choices determined by the story-teller (causality) and the formal model created by the observer (encoding–inference–decoding).

We argue that in the case of nuclear narratives, there is no semantic closure of the formal representations used. As shown in the previous section, the representation of nuclear power as a viable alternative energy source is based on the beliefs that, for example, electricity produced with nuclear power plants will be too cheap to meter, that nuclear power plants can be made safer in response to accidents, and so on. These beliefs are translated into models used to design nuclear power plants. However, experience shows that the construction and running of nuclear power plants have considerable costs, and that the large scale and long time required to build nuclear power plants makes existing plants irresponsive to new safety requirements and lead to a situation of technological lock-in. This lack of consistency between expectations and experience indicates a lack of semantic closure in the models used.

Section 3.2 shows how the step of the validation of the narrative through decoding simply does not take place in the governance of nuclear power, implying a series of mismatches between perception and experience about nuclear power and contributing to explain the controversy.

3.2. The concept of holon and the lack of semantic closure of nuclear energy systems

In order to explain how models are used to guide action in the case of nuclear power, we use the conceptual tools of complexity theory. Energy systems can be defined as complex systems in so far as they have to be described using multiple scales of analysis (such as the availability of primary energy sources related to the ecosystem, and the production and use of energy carriers related to the internal structure of the society) that are non-equivalent and non-reducible to each other (Diaz-Maurin and Giampietro, 2013b). Complexity theory thus provides a useful problem framing for the representation of energy systems.

More specifically, hierarchy theory—a branch of complexity theory (Allen and Starr, 1982; Ahl and Allen, 1996)—introduces the concept of *holon* used to describe an entity that can be perceived both as a whole and as a part (Koestler, 1968). That is, holons have a fuzzy identity, which can be described both through the external view (looking at the interactions between the whole and its context regulated by thermodynamic laws) and through the internal view (looking at the parts of the system regulated by codes and systems of controls). Consequently, the concept of holon makes it possible to take into consideration the multiple scales of analysis required in order to perform an integrated assessment of complex energy systems.

When dealing with a holon one is dealing with something that is a realization subject to laws (Pattee, 1978), and at the same time with something that is just information. The holon is a conceptual tool, not a physical entity, used to describe the iteration between the realization and the linguistic definition, or between experience and narrative (Allen and Giampietro, 2014). The holon acts as *the skin of the system* by defining the level of observation. The concept of holon is very useful when studying complex entities that can be described at various levels (both temporal and hierarchical) and by different observers, as is the case of nuclear power.

From the point of view of the holon, the semiotic process can be divided into four stages recalling Rosen's modeling relation (Giampietro, 2003). First, the system is constituted by the realization of a plan (*constructing*) that must be compatible with the availability of the favorable gradients (external constraints). Second, the outputs generated by the system tell a story (*narrating*) to which the external world reacts by sending an input (feedback) to the holon (e.g. declining resources or new types of threat). Third, inputs from experience impose a change in plan to the system so that the holon becomes something else (*becoming*). Last, the whole functioning of the holon is experienced by an external observer (*observing*).

As shown in Fig. 2, the four steps of the semiotic process of a holon (observing, constructing, narrating, and becoming) work at different rates (dT, dt, $d\theta$ and $d\tau$ respectively), corresponding to different time scales at which the system can be perceived (Giampietro, 2003). As a consequence, the knowledge generated about the holon depends on the choice of narrative and on the choice of temporal scale when constructing a model. We provide two examples of narratives, the engineering view and the metabolic view, and their relative temporal scales.

According to the engineering perception of nuclear power, new reactor designs are implemented (process of *constructing*, $dt \approx 10$ years). Then, the physical realization of the system is checked against external constraints (e.g. new failure modes) and provides a feedback (e.g. higher magnitude of natural events) to the semantic part (process of *narrating*, $d\theta \approx 8$ years (Diaz-Maurin, 2011; Ha-Duong and Journé, 2014)). From this experience, the representation of the system evolves (process of *becoming*, $d\tau \approx 10$ years) implying changes in the plan. As the engineering view on nuclear power focuses on reactor safety design, the time horizon of analysis corresponds to the plant lifetime (process of *observing*, $dT = 35–40$ years). The main problem of the plant-level representation of nuclear power is that it disregards other relevant time scales. That is, by adopting the engineering narrative about nuclear power ($dT = 40$ years), it is impossible to *observe* what happens at larger time scales (e.g. long-term waste management). In this specific case, nuclear reactor engineering focuses on the process of *constructing*, letting aside the aspects related to the meaning of the system (*narrating* and *becoming*).

Nuclear power can also be perceived from the *societal metabolism* perspective (Diaz-Maurin, 2013). Societal metabolism refers to the description of the processes through which society reproduces itself (Giampietro et al., 2011). An analogy is established between the consumption of energy, water and other materials by a societal system and the metabolization of food by the human body. In the analogy, energy consumption is studied in relation to its function in reproducing specific human activities.

The time horizon of analysis required when adopting the societal metabolism view (dT of about 100 years) is longer than the one required by the engineering view (dT of 35–40 years) as it

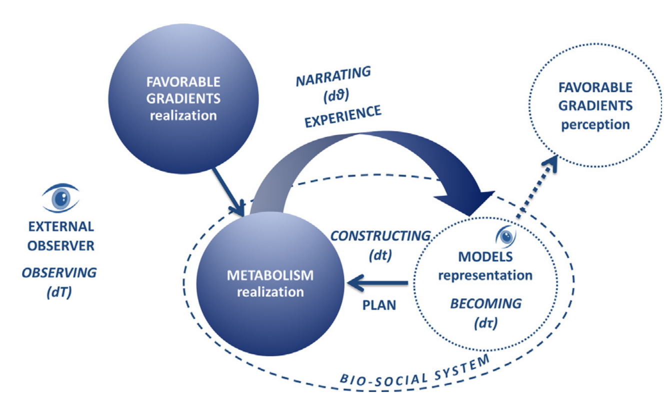

Fig. 2. General functioning of the semiotic process of the holon of a bio-social system.
Source: Adapted from Allen and Giampietro (2014).

corresponds to the average time of an energy transition (a large scale shift to a different mix of primary energy sources (Smil, 2010b)). In the case of nuclear energy systems, this corresponds to the transition of the overall nuclear-fuel cycle (Kazimi et al., 2011). This shift in the time horizon exceeds, by far, the capability of human societies to organize themselves around such long time periods. This limitation is mainly due to the unavoidable expiration date of available information about the characteristics of local processes over a long period as well as the inescapable limit set by the life expectancy of human beings, letting alone the issue of fast-changing political goals at shorter time periods.

Moreover, when considering the long-term management of radioactive waste, $d\theta$ becomes equal to thousands of years, whereas the time of observation dT cannot practically be longer than 100 years. There is an incompatibility between the process of *narrating* and the process of *observing* due to the very long time required by the nuclear energy system to provide feedback in relation with waste management ($d\theta \gg dT$). This incompatibility between $d\theta$ and dT is the most critical issue over the time rates involved with nuclear power as it affects the ability of this energy system to provide feedbacks within the time horizon of observation.

As we have shown, the various possible choices over the time horizon of the analysis affect the resulting description of the nuclear energy system and, most importantly, the formalization of its relevant attributes. It should be noted also that due to the difficulty of human societies to re-organize themselves over a different identity (something that is mandatory when considering long time periods), there is a tendency to adopt perceptions of the process of interaction with the external world that require shorter time horizons. This is the reason why the engineering narrative about nuclear power is often given priority over the societal metabolism narrative. For example, reducing the health risk of nuclear power to the immediate number of fatalities—the so-called "death toll"—in case of reactor accident privileges a short time horizon (Diaz-Maurin, 2013, 2014).

The choice of narrative has serious implications for the governance of nuclear energy systems. The short time horizon used by the engineering perspective does not take into account relevant attributes that act at lager time scales, making it impossible to achieve semantic closure. Given this failure, it is important to study the reasons that may explain the continuous reproduction of the nuclear power industry by looking at the relations between narratives and experiences.

The perception and the development of technology go hand in hand and reinforce each other so that narratives may drive the development of a technology and, at the same time, be the result of the new applications and uses of this technology. In the case of nuclear power, one can observe how experience (e.g. unavoidable reactor accidents (Perrow, 1984, 2011; Pidgeon, 2011)) affects the development of technology, and how technology drives the emergence of new narratives (e.g. "too cheap to meter"). The fact that nuclear power is largely deployed, in spite of the multiple negative feedbacks received from experience, clearly indicates the existence of complex interactions between narratives and experiences.

4. Dominant Narrative Analysis of nuclear power in the United States

In this section, we provide a dynamic representation of the history of nuclear power by mapping the main actors and related narratives identified in Section 2 into a three-dimensional space using a representation based on the theoretical framework presented in Section 3. This analysis shows how the controversy over nuclear power is due to the complex relations between changing and emerging narratives and experiences over time.

Allen and Giampietro (2014) suggest a way of dealing with the process of changes in time of the narratives used in the evolution of holons by plotting the cycle of meaning and realization of the holon along a spiral. Fig. 3 presents the spiral definition of the evolution of a holon which captures the three steps shown in Fig. 2. Putting the *becoming* process along the axis of the figure makes it possible to keep track of subsequent acts of becoming something else. That is, Fig. 2 is a flat circular version of Fig. 3 where changes in the meaning and realization of the system happen around a loop. One loop of the spiral illustrates the evolution of the holon from the old narrative to the new updated narrative.

Each time the narrative is updated, it gives the system a new becoming. The execution of becoming something different corresponds to the next loop. The story-teller sees the holon changing its story at a rate $d\tau$, while her own identity is changing at rate $d\theta_{nr}$. The corollary is that the identity of the holon can be described by the story-teller at rate $d\theta_{nv}$. As the dominant narrative is always being updated in time, the realization of the system cannot be defined once and for all.

Based on the historical background provided in Section 2, and using the representation described above, we can now track how the narratives of the different actors have evolved according to experience. We call this representation a "Dominant Narrative Analysis" as the spiral definition of the holon recalls the schematic representation of the structure of DNA of living systems used in genetics. Dominant narratives are revealed by looking at which narrative was turned into realization at different points in time. For this representation, we focus on the US. A similar analysis could be conducted for other countries based on a historical overview of the main actors and related narratives.

It should be noted that any exercise such as this one is unavoidably biased by the identity of the analyst (in this case the authors of this paper). For this reason, the analysis provided below does not provide a full refinement of all possible relevant narratives that existed throughout the history of nuclear power in the US. The objective here is to check whether from this coarse grain analysis, some insights can be obtained to explain the continued existence of nuclear power despite its negative feedbacks.

Fig. 4 presents the sequential evolution of the holon of the nuclear energy system in the US from 1939 to 2011. It maps the main actors and related narratives identified in Section 2 following the "expected-established-experienced" function described in Fig. 3 (turned ninety degrees clockwise to fit within the formatting requirements of the journal).

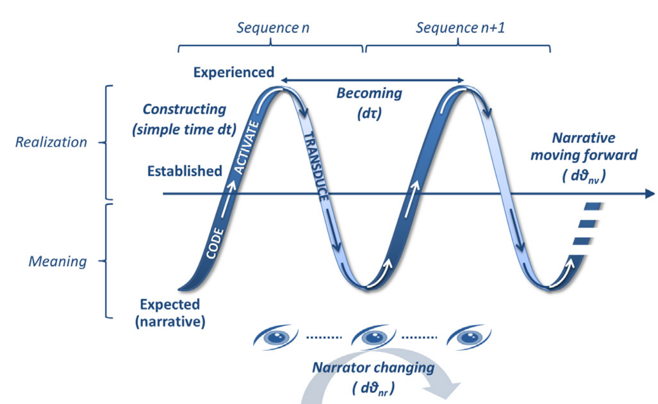

Fig. 3. The spiral representation of the semiotic process used in the Dominant Narrative Analysis (after Allen and Giampietro, 2014).

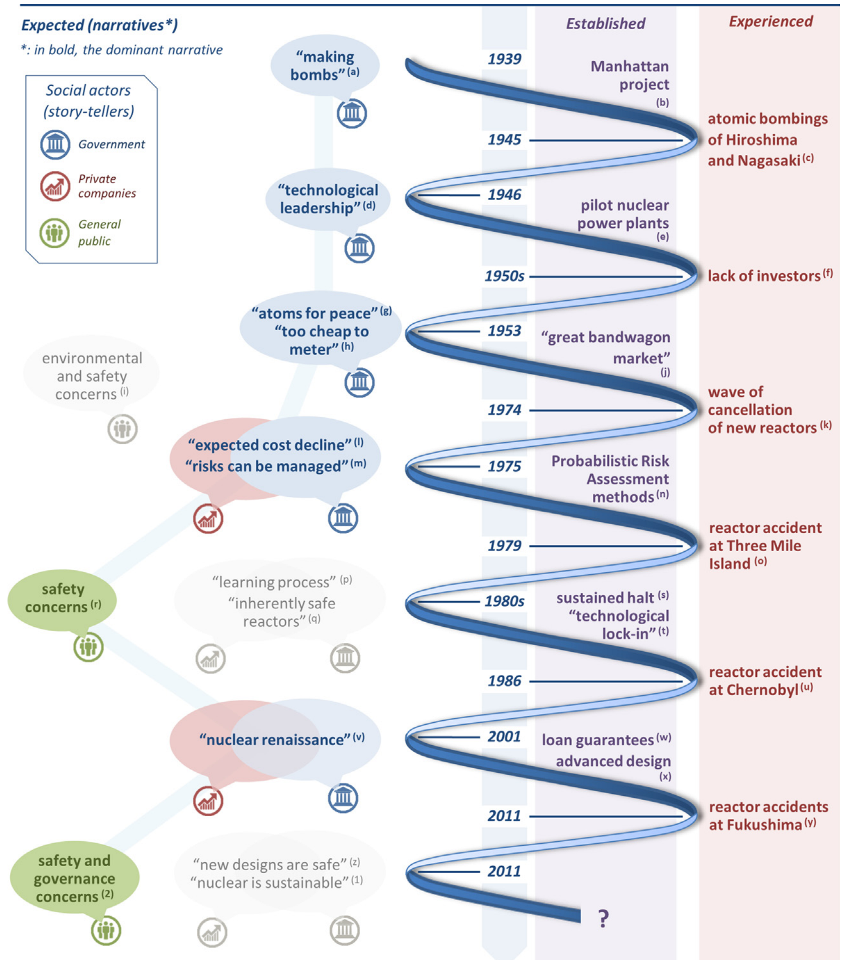

Fig. 4. Dominant Narrative Analysis of nuclear power in the United States (own elaboration). *Note*: (a) "making bombs" (Einstein and Szilárd, 1939); (b) Manhattan project (see http://en.wikipedia.org/wiki/The_Manhattan_Project, accessed 29 Sep 2014); (c) atomic bombings of Hiroshima and Nagasaki (see http://en.wikipedia.org/wiki/Atomic_bombings_of_Hiroshima_and_Nagasaki, accessed 29 Sep 2014); (d) "technological leadership" (Duffy, 2004); (e) pilot nuclear power plants (Bodansky, 2004); (f) lack of investors (Duffy, 2004); (g) "atoms for peace" (Eisenhower, 1953); (h) "too cheap to meter" (Strauss, 1954); (i) environmental and safety concerns (Carson, 1962; Duffy, 2004); (j) "great bandwagon market" (Bupp and Derian, 1978); (k) wave of cancelation of new reactors (Bodansky, 2004); (l) "expected cost decline" (Bupp and Derian, 1978); (m) "risks can be managed" (Rasmussen et al., 1975); (n) Probabilistic Risk Assessment methods (a discussion in Diaz-Maurin, 2013); (o) reactor accident at Three Mile Island (see http://en.wikipedia.org/wiki/Three_Mile_Island_accident, accessed 29 Sep 2014); (p) "learning process" (e.g. Joskow and Rozanski, 1979); (q) "inherently safe reactors" (Weinberg and Spiewak, 1984; Weinberg et al., 1985); (r) safety concerns (Perrow, 1984); (s) sustained halt (Bodansky, 2004); (t) "technological lock-in" (Arthur, 1989; Cowan, 1990); (u) reactor accident at Chernobyl (see http://en.wikipedia.org/wiki/Chernobyl_disaster, accessed 29 Sep 2014); (v) "nuclear renaissance" (Nuttall, 2004; Grimes and Nuttall, 2010); (w) loan guarantees (Deutch et al., 2003); (x) advanced designs (WNA, 2013; see also http://en.wikipedia.org/wiki/Generation_III_reactor, accessed 29 Sep 2014); (y) reactor accidents at Fukushima (Diaz-Maurin, 2011; see also http://en.wikipedia.org/wiki/Fukushima_Daiichi_nuclear_disaster, accessed 29 Sep 2014); (z) "new designs are safe" (Clery, 2011; Bullis, 2011); (1) "nuclear is sustainable" (WNA, 2009); (2) safety and governance concerns (Pidgeon and Demski, 2012; Bidwai, 2011).

Fig. 4 shows that the identity of the nuclear energy system in the US is described in the first sequence with the use of nuclear energy for military purposes during WWII. The political dimension remained the only relevant dimension governing nuclear affairs until the early 1950s, hence making the government the dominant actor. Since 1965, the public started to express environmental and safety concerns over the deployment of nuclear power. However, the government remained the dominant actor given the large-scale nature of the deployment plan. This plan generated sufficient interest for private companies to enter into the debate from 1975 onward. This created in turn a *collusion* between the government and the private sector, which has been maintained to date. Every time the meaning of the system has forced a change due to negative feedbacks from realization, the two actors have been able to update their narratives accordingly, maintaining the collusion.

This collusion between the two dominant actors—characterized by a shared positive perception of nuclear affairs—has made possible the survival of nuclear power through the various crises it experienced since the 1980s. The government perceives nuclear power as a powerful stabilizing factor of the status quo (for military reasons and for the deep dependence on regulations and security activities). The private sector also perceives publicly subsidized nuclear power as a stabilizing factor of the status quo. Mega projects funded by public money guarantee a situation of quasi-monopoly with guaranteed revenues to corporations in the business, that is, if something bad happens the costs will be paid by tax payers (O'Connor, 1973; Stiglitz, 2011). The existence of such collusion is so crucial for the survival of this technology that the two actors are in some cases merged into one unique conglomerate of institutions. This is the case in France where the nuclear power industry is state-ruled, which has facilitated—and even made possible—the continued deployment of this technology throughout the period of global slow-down in the 1980s and 90s.

In the 1980s, although the view of public opinion mainly characterized by safety concerns (fifth sequence) became seemingly dominant after the Three Mile Island accident, the driving force behind the nuclear affairs was still the economic dimension. This is why the expression ‘‘technological lock-in’’ is often used when referring to the fact that nuclear power had not disappeared after the halt of the mid-1970s. Because of the long return on, and size of, the investments required to build and maintain the nuclear industry, nuclear power inevitably creates a lock-in situation, which reactor vendors and utilities were the first to be affected by.

When looking at the last sequences of the holon of nuclear power since the 1970s, the economic and safety narratives seem entangled in a vicious circle/virtuous cycle (depending on the context and the actors' contrasting perceptions) of dominant dimensions. On the one hand, the systemic problem of non-viability of nuclear power can be explained by a choice of technology (e.g. Weinberg and Spiewak, 1984; Weinberg et al., 1985) driven by underlying military purposes creating problems with its fuel cycle (e.g. Kazimi et al., 2011) and even a delusion (e.g. Proops, 2001; Mayumi and Polimeni, 2012). On the other hand, the systemic problem of safety comes from an incompatibility between model-based claims from the nuclear industry and the perception of risks from the public opinion driven by distrust and misinformation (Diaz-Maurin, 2013).

5. Discussion

The dominant narrative analysis of the history of nuclear power presented in this paper reveals several characteristics of the narratives surrounding nuclear power.

First, it can be observed that after a difficult creation of the nuclear energy system throughout the 1940s and 50s, the system has mapped to a set of perceptions shared by a collusion between government, electric utilities and reactor vendors. The collusion made possible the realization of the nuclear power industry at the end of the 1960s. This collusion gave the nuclear energy system a striking ability to update its narratives at fast pace depending on the input received from the experience. To any unexpected and adverse event experienced by the nuclear energy system, there is an almost immediate reaction as to what the new realization of the system should be (Fig. 4 is not to the scale). For example, few days after the Fukushima accidents happened, some were already claiming that new designs were safe (e.g. Clery, 2011; Bullis, 2011).

Second, the narratives used to justify a positive perception of the nuclear energy system have been continuously updated in response to negative feed-back coming from the ‘‘experienced’’ step. The corollary of this proposition is that, even when the public questioned the dominant view (e.g. in the current post-Fukushima era), the realization of the nuclear energy system has been delayed but never stopped.

Third, the problem of the current pro-nuclear narrative in relation to sustainability lies in the fact that it would be impossible for the system to generate full experience in relation to the sustainability dimension. This would require anticipating, (1) on the supply side, the decline of uranium resources (similarly to the problem of declining fossil energy resources, this task is difficult since it refers to a long time horizon); as well as (2) on the sink side, the long-term management of radioactive waste, a task that is even more complicated as it requires thousands of years and is incompatible with the maximum time horizon human beings are able to consider for their own survival (Shrader-Frechette, 2000).

The lack of semantic closure in the governance of nuclear power can be seen in a series of mismatches between perception and experience about nuclear power that explains its controversy. In the discourse over cost effectiveness, for instance, the government defines the relevant perception, in describing the emerging technology as a great opportunity for producing cheap electricity (‘‘too cheap to meter’’), while reactor vendors and electric utilities experienced increasing costs of construction and maintenance and insufficient gains to sustain profits. The result of this mismatch led to the decline of nuclear energy between the 1970s until the 1990s. The environmental discourse sees private companies adopting the narrative of nuclear energy as a clean energy source that can help fight climate change, whereas the public experiences that nuclear energy implies harmful consequences for humans and the environment because of accidents and the problematic handling of waste.

Looking at this series of mismatches one can conclude that the main problem lies with the scientific information used, which does not help resolve the controversies. Models can provide accurate quantitative information. However, their validity depends on the *ceteris paribus* assumption implied by a fixed choice of scale. On the contrary, narratives are very useful for studying how complex systems are becoming over time, thanks to their ability to handle changes in the original definitions of scale (Allen and Giampietro, 2014). We argue that the issue is, whether models are developed within a useful narrative—which further leads to the question, useful according to whom?

The lack of semantic closure in the production and use of scientific knowledge about nuclear energy systems results in a belief-based practice that is irresponsive to feedbacks from the experience or to the emergence of new narratives (such as anti-nuclear social movements). For this reason, nuclear power can be seen as a ‘‘belief-based’’ technology (Yang, 2009).

The controversy about nuclear energy can be explained as the result of two factors. First, the various narratives at stake are based on non-equivalent levels of observation and on incommensurable values so that the holon of nuclear power cannot be defined through a single temporal scale or a single set of criteria. Second, the evolution of the holon of nuclear power has never reached—and cannot reach—semantic closure because of the disconnect between the beliefs—upon which perceptions about the desirability and viability of nuclear power are based—and the realization of the system—constrained by thermodynamic laws. Therefore the systemic controversy over nuclear power may be treated as a problem of contrasting beliefs and normative stands in disjunction from experience.

6. Conclusion

The unavoidable global trend toward a progressive depletion of energy resources explains the revived interest from the scientific community over the energy-supply issues in recent years (e.g. Murray and King, 2012; Kerr, 2012).

The issue of energy-supply requires dealing with the critical appraisal of the potential of alternative energy sources to power modern societies. Yet, since any quantification depends on a pre-analytical (arbitrary) choice of narratives about what is feasible and desirable, more attention should be given to the quality of the narratives used in policy making.

The analysis of narratives helps put semantics—the consideration of meaning and purpose—back into the technical discussion over the viability and desirability of nuclear power. The question of usefulness and relevance of the chosen representation can be addressed by making the role of the analyst explicit, both in their role as story-teller defining the relevant perceptions and as observer defining the relevant representation. This approach helps clarify the possible inadequacy of the representation used with respect to what is experienced, which is especially useful to study the governance challenges of nuclear power. We believe that the approach offered in this paper could also be useful to study other controversies.

The existence of a collusion between the dominant actors shown in this paper, able to carry on nuclear deployment plans despite the negative feedbacks, has reinforced the belief that nuclear power is a desirable technology "by default". This has been made possible by systematically assessing the viability and desirability of nuclear power in relation to narratives about its *future*, overlooking the mismatch with its observed present realizations. For this reason, more attention should be given to the quality of the narratives used in policy making. The analysis presented in this paper shows that the narratives used to justify the deployment of nuclear power, based on the engineering view, are at odds with experience (increasing costs, accidents, waste handling) and in contrast with alternative narratives based on a larger time scale.

This serious epistemological gap explains why nuclear power is still seen within the dominant narrative as the "last best option" in the discussion over the energy-supply issues (Schnoor, 2013). This illustrates the ideological intoxication of the positive perception over nuclear power. By privileging the future over the present, policy-makers cannot get rid of their imagined conception and build a fresh perspective on this technology. Consequently, the effects of energy-supply shortages on the functioning of the society are left out of the planning. We argue that when looking for alternative energy sources, policy makers should avoid closing the option space in situations where facts are uncertain and values are in dispute (Funtowicz and Ravetz, 1993). In addition to technological improvements, the quality of the narratives used for policy should also be improved by cross-checking the narratives used and looking for consistency between expectations and experience.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2015.01.014.

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