TENTATIVE IDEAS TO EXPLORE THE VIABILITY OF THE NUCLEAR OPTION

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ABSTRACT

After the accidents at nuclear reactors of Three Mile Island (United States, 1979) and Chernobyl (Ukraine, 1986), the world has turned its back on the civilian nuclear industry. Since then, developing energy from nuclear sources had been widely abandoned, with a few exceptions, such as France. his has resulted in a *quasi*-moribund nuclear industry until the end of the 20th century. However, the early 21st century has created some circumstances that have changed the way countries regard the nuclear option when considering their mix of Primary Energy Sources.

Despite the turbulent times of the economic crisis, industrialized countries are looking for alternative energy sources in order to break the addiction to fossil energy, as well as to achieve energy independence. On the other hand, the global energy demand keeps rising, especially because of the economic growth of emerging countries. This is enough for the nuclear option to be seen as the energy source the most likely to overcome these challenges, so much so that some talk of a 'nuclear renaissance'. Indeed, nuclear energy proponents market it as an alternative energy, even sometimes calling it *sustainable*, able to produce 'CO_2-free', or 'zero-emission', energy that is available in large quantities, stable in terms of safety and security, and economically competitive.

However, I argue that the nuclear option is more a choice of circumstance rather than a result of a collective and social debate. Moreover, the new craze for nuclear energy seems to be based on old narratives about energy and sustainability. Consequently, it must be reconsidered whether or not nuclear energy is actually an alternative energy source. In other words, it must be verified whether or not this technology is viable. That being said, it shall be conceded that analyzing the feasibility of the nuclear technology is made difficult by the diversity of structures and functions involved in such a complex socio-economic system.

Nevertheless, recent discussions about energy and sustainability offer some tools to better frame energy analysis. In this paper, I will try to explore the possibilities of adopting the MuSIASEM scheme (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism), developed by Giampietro and Mayumi, as a framework to examine the feasibility and desirability of the nuclear option. As a starting point, I will try to identify the different concepts and variables to consider, especially the different parameters, scales, and criteria of performance. The reader will be also invited to provide critiques and advices based on these tentative ideas since particular attention must be paid to the definition of such a multi-scale integrated analysis. This is especially important since it intends to pave the way for a serious discussion about the future of the nuclear option as an alternative energy source.

Keywords: Nuclear Energy, Sustainability, Viability, Multi-Scale Integrated Analysis, MuSIASEM

1. INTRODUCTION

Nowadays, we certainly live a critical moment in which modern society depends more than ever on energy supply. At the same time the biosphere shows us that its resources are limited which is a fact that has been globally acknowledged only relatively recently. For that reason, the question of energy has become probably one of the most critical issues humankind will have to face during the 21st century. People in charge of finding solutions to this issue will be challenged as they will have to account for external

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constraints (e.g. limits of the natural resources) as well as internal constraints (e.g. increase of population and energy consumption per capita). The existence of such constraints brings its share of questions whether it is actually possible to meet the future energy needs of humanity while being forced to accept the finiteness of the natural resources, or put in other words, the limited speed of the planet's capacity for regeneration.

Moreover, the current situation is not urgent only because of those constraints but also because our dependence to fossil energy has led to a human-driven climate change. This has become even worse due to the decrease of natural resource quality; so that we need more Primary Energy Sources to produce the same amount of Energy Carrier than in the past [Hall, 2008]. Therefore, the main challenge clearly is environmental and the question of energy is all about finding a path toward ecological sustainability when dealing with energy supply.

Given this challenging situation, some people have been looking for sources that are able to supply our needs for large amounts of energy, and so, for several decades. That is mainly the reason why nuclear energy has come back to the foreground of the debate about alternative energy sources to succeed to the fossil energy era.

2. STUDYING THE VIABILITY OF NUCLEAR ENERGY AS AN URGENT ISSUE

2.1. About the future of energy

As of today, there is no obvious solution to solve the question of energy, since every energy source has its pros and cons. As a result, the most viable alternative energy source may vary depending on which criteria of performance we give priority to. For instance, if we consider that the most important is to provide large amounts of energy, nuclear energy sounds to be a good candidate. On the contrary, if we want to minimize the danger related to the wastes coming from the energy production process, nuclear energy becomes right away less attractive. We will see later that (1) the criteria of performance need to come as a result of the public debate; and (2) the assessment of the viability of an alternative energy is more complex than a linear study as the previous sentence could have suggested.

As a matter of fact, studying our energy future is all about trade-offs between the different alternative energy sources so that the *solution* will certainly be a mix of those different energy sources. Having said that, the question now is whether every alternative energy sources should actually be part of the energy mix and, if so, with which balance.

2.2. Nuclear energy as a good candidate…

Given the current circumstances described above, nuclear energy is more and more seen as one of the energy sources most likely to solve the question of energy. Indeed, at first sight the simple equation is that the nuclear energy production process seems to be able to supply large amounts of energy using natural resources (uranium) that will be available at least through the 21st century [Deutch et al., 2003; Kazimi et al., 2010]. The new generation of nuclear power plant is also announced as being safer with a reduction of the probability of nuclear accident, while control measures can be taken in order to make the nuclear fuel cycle more secure in terms of proliferation [Deutch et al., 2003]. Now, if we add to this equation the fact that “nuclear power can potentially contribute significantly to reducing global warming” [Deutch et al., 2003], then we start to understand how much nuclear energy becomes a serious candidate, if not the most appealing one, in such a debate about alternative energy sources. Nuclear energy is finally often marketed by its proponents as an alternative energy able to produce ‘carbon-free’ energy that is available in large quantities, stable in terms of safety and security, and economically competitive.

2.3. …but no consensus yet

At the same time, the possible deployment of the nuclear technology could be more difficult to achieve than expected given all the efforts that need to be made prior to its success. Indeed, some challenges have already been identified as required to be overcome if nuclear energy wants to play a role in the future of energy: the high up-front capital costs of the nuclear production processes, or the large amount of research efforts that remain to prove the regulatory feasibility of new designs as well as to find a long term management solution for high level wastes [Deutch et al., 2003] are only a few examples. And most of those challenges have remained until recently [Deutch et al., 2009]. In short, as Hall and Powers [2008] say, there are "great potential gains and great potential costs with nuclear power".

Hall and Powers [2008] also remarkably pointed out that the ongoing opposition about nuclear energy is due to the fact that nuclear energy optimists rely on technology to overcome those challenges while nuclear pessimists mainly focus on uranium depletion to demonstrate that it would probably not be possible to overcome those challenges. This opposition demonstrates how strong the opinions about nuclear energy are, being positive or negative, which impact current studies about nuclear energy. As a result, Hall and Powers [2008] conclude that "only empirical analysis can assess the potential future of nuclear power". However, we argue that performing an empirical analysis about nuclear energy actually means reaching a deadlock. Indeed, although empirical data are definitely necessary to any energy study, the problem with nuclear technology is that (1) empirical data can only be collected on a large number of plants in order to compare them, so once a given technology has already been developed and its deployment has already been engaged; and (2) those plants use different production processes from which data would not be directly comparable. As a result, studies about nuclear energy using empirical data are always performed once the necessary financial and human capitals have already been invested to the development and deployment of a new technology. Therefore, empirical studies can only assess the viability of current or past nuclear technological choices and cannot assess future production processes that are still under development which is contradictory with Giampietro et al.' [2010] suggestion that "it would be wise to perform a *quality check* on the discussion of the future energy scenarios, by combining the old wisdom and the recent development in the field of energetics, before investing billions of € and US$ on very dubious alternative energy sources".

Lastly, there is no much doubt that there is still a large disagreement about the viability of nuclear energy, so much so that there is a risk of launching a new nuclear deployment before verifying its potential advantages. For that reason, assessing the viability of the nuclear option as part of the potential alternative energy sources is something that seems to be necessary and that has not been performed to date.

2.4. The problems encountered in current studies about nuclear energy

Existing energy studies about nuclear technology, even the most recent ones, present some analytical problems that right away put into question their conclusions and explain why there are so many discrepancies between their results. Those problems seems to differentiate themselves into two categories such as analytical problems (wrong assumptions) and conceptual problems (wrong methodology), with some studies cumulating both types of problems.

2.4.1. Analytical problems

Analytical problems occur when a given study mistakenly considers assumptions that are either not correct or not adapted to the study. This is illustrated by the disparity of the results found in studies that intend to have the same purpose, and apparently use the same methodology. For instance, studies assessing the life cycle carbon emissions of the nuclear energy production process published results from no less than 1.4 carbon dioxide equivalent per kWh (gCO2e/kWh) to 288 gCO2e/kWh [Sovacool, 2008]. According to Sovacool [2008] who analyzed more than one hundred studies about the nuclear energy life cycle, these differences are due to the fact that lower bound studies miss some steps of the nuclear energy life cycle (e.g. plant construction, decommissioning fuel transportation, etc.), while upper bound studies consider unrealistic assumptions about the nuclear technology (e.g. nuclear power plant operation lifetime overestimated, outdated uranium enrichment process, etc.).

This type of problems is also at the origin of the discrepancy observed in studies evaluating the Energy Return On Investment (EROI) of nuclear energy, i.e. the ratio between the amount of energy delivered to the society (mainly electricity considered as the Energy Carrier) and the amount of energy put into the conversion process (considered as the Primary Energy Source) [Giampietro et al., 2010]. Indeed, published results go from an EROI less than 10:1 up to 60:1 [Hall and Powers, 2008], even 93:1 according to a study of the University of Melbourne [Sevior, 2010]. As Hall and Powers [2008] say and others already observed in previous studies, “this discrepancy on the EROI figure for nuclear has to be clarified as one of the most urgent energy issue”.

Those analytical problems seem to have two main origins related to the analyst or team of analysts who performed those studies: (1) lack of expertise about the nuclear energy production processes and different technologies; (2) lack of objectivity worsened by the existence of an *a priori* opinion that affects the integrity of the study and thus its results. Reibstein [2003] gives us a partial explanation to that problem as “critical experts on radiation injury, nuclear weapons proliferation, nuclear waste, operational accidents, nuclear materials, mining and refining, and alternative sources of energy do not have the money and institutional context of the nuclear proponents” which reduces the number of critical studies about nuclear energy. On the contrary, experts from the nuclear industry are certainly more likely to be nuclear optimists since it would be difficult for them to publish results that go against the nuclear energy deployment. As Upton Sinclair used to say “it is difficult to get a man to understand something when his job depends on not understanding it”. In short, they have an irrevocable conflict of interests which undermines the objectivity of their studies. On the other hand, opponents who have performed critical studies about nuclear energy are not always familiar with the nuclear industry so much so that they do not have the necessary expertise to avoid the analytical problems identified above. This justifies, if still necessary, the fact that a serious discussion, in terms of objectivity and expertise, must be engaged about the viability of nuclear energy.

2.4.2. Conceptual problems

Conceptual problems deal with the methodology used to perform an energy study, in terms of energy accounting for example. As of today, except studies that would have been missed here, it seems that there is no study that addresses this kind of problems. Indeed, most of the existing studies adopt a conventional linear view of the exploitation of Primary Energy Sources [Giampietro et al., 2010] which appears useful in some ways but certainly not sufficient to assess the quality of an energy source as described later in this paper. Indeed, a linear approach of energy accounting entails some reductionisms that affect the pertinence of the quantitative results. Such effects of considering a linear view in energy accounting are discussed in Giampietro et al. [2010].

Although some studies use a net energy approach to energy accounting which partially addresses the conceptual problems we just described (e.g. by performing an EROI evaluation), we found out that other conceptual problems remain.Indeed, existing studies about sustainability do not address the issues of scale, dimensions and/or time, and thus do not give a full picture of the nuclear energy production process since (1) they do not give meaning to their results in relation to different functions of the society (scales); (2) they assess only few criteria of performance (dimensions) without cross-referencing their results; and (3) they do not take into account qualitative changes over time.

A good way to illustrate those remaining conceptual problems is looking at how much not considering the qualitative changes over time can affect the results of a given energy study. For instance, existing studies that intend to assess the availability of the natural uranium ore supply in the future often conclude that natural uranium will be available until the end of the century at reasonable price [Deutch et al., 2003; Kazimi et al., 2010], but never take into account the fact that the quality of the uranium ore (natural enrichment) will decrease over time, which will automatically increase the amount of 'energy for energy' used in the same production process. Put in other words, in that case the EROI is more-likely to decreased over time as technological improvements are much likely not to be able to offset this drop in the quality of natural resources.

As a matter of fact, it seems that there is a gap in the research about nuclear energy in terms of its viability and a serious discussion needs to be engaged. Now, the question is how to perform such an assessment of the viability of nuclear energy as an alternative energy source.

3. VIABILITY OF AN ENERGY SOURCE

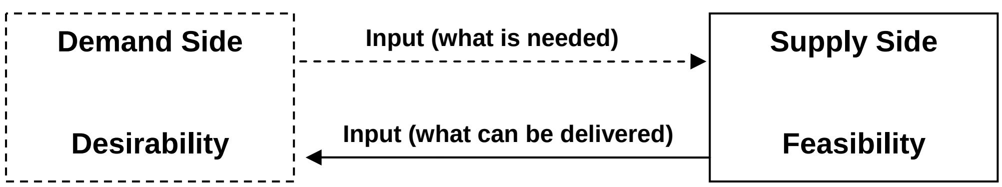
3.1. Feasibility vs. desirability

It is now time to formally define what we meant so far when speaking of the viability of an energy source. The viability of an energy source corresponds here to its quality. As explained by Giampietro et al. [2010], in order to discuss the quality of energy sources it is essential to be able to visualize and quantify the characteristics of the metabolic pattern in two independent ways providing a definition of the quality from the supply side (what can be delivered) and from the demand side (what is needed). In other words, assessing the quality of an energy source – or its viability – implies looking at its feasibility as well as its desirability. Indeed, the feasibility of a given technology represents the assessment from the supply side, while its desirability represents the assessment from the demand side.

Going further, the feasibility of a given technology can be assessed only after having decided a particular form of the metabolic pattern from the demand side, while the desirability can be assessed only after having decided a particular form of the metabolic pattern from the supply side [Giampietro et al., 2010]. Therefore, the discussion of the quality of an energy source is, in some ways, a chicken-egg problem in which assessing one side requires the other side already being assessed, and *vice versa*, as illustrated in Figure 1.

According to Giampietro et al. [2010], it is necessary to simultaneously look at the two sides when studying the energetic metabolic pattern of modern society, because assessing the quality of an energy source is all about matching the supply side with the demand side. According to the authors, this approach corresponds to a heuristic method intending to overcome the simplifications which imply reductionism and that are usually in use in standard quantitative analyses of energetic metabolic pattern of society. This is all the more important since discussing the quality of an energy source especially implies performing a quantitative analysis. As far as the chicken-egg problem cited above, we will discuss later in this paper how do deal with this issue by adopting the MuSIASEM analytical tool so that this issue can be turned in a way to test the robustness of the quality assessment of a given energy source.

Figure 1. The Chicken-Egg Problem of the Viability Assessment



3.2. Purpose of a viability assessment

As explained before, the quantitative assessment of the viability of nuclear energy is necessary since this technology intends to be an alternative energy source. Now, as Giampietro and Sorman [2009] rightly pointed out, "the pre-analytical definition of the purpose of the analysis will determine the usefulness and pertinence of the quantitative results". In other words, it is important to provide a clear explanation of the purpose of such a discussion about the quality of a given energy source before actually performing the analysis. The general purpose of a viability assessment is to provide quantitative results of the feasibility and desirability of a given energy source as a support to the public debate about alternative energy sources. Indeed, the public debate consisting in comparing different possible energy scenarios cannot be done without the support from quantitative scientific studies. On the contrary, scientific studies cannot and should not fully assess the quality of an energy source without the participation of the society as a whole in selecting, even indirectly, the criteria of performance considered as being the most relevant. Indeed, a "scientific analysis cannot and should not be used to answer the question about sustainability (sustainability of what?; sustainability for whom?; sustainability for how long?). his is the role of humankind as a whole which has to decide how to deal with the semantics of sustainability" [Tainter, 2008; in Giampietro et al., 2008]. In general terms, it is not the role of scientific studies to answer questions from the demand side. Nevertheless, scientific studies can *help* answering those questions which should be the purpose of any analysis intending to assess the quality of an energy source.

4. TENTATIVE IDEAS TO ASSESS THE VIABILITY OF NUCLEAR ENERGY

We previously argued why having a serious discussion about nuclear energy is urgent, and what assessing the viability of an energy source actually is. Now, here are some tentative ideas, presented as successive steps, on how we could perform such an assessment of the potentiality of nuclear energy as an alternative energy source.

4.1. Step 1. Critical appraisal of the existing literature on EROI of nuclear energy, and generation of a new EROI analysis

A new EROI analysis about nuclear energy seems to be necessary given the discrepancy of existing results due to the analytical problems found in existing studies as we discussed before. As a preliminary step to this analysis, an exhaustive overview and critical appraisal of the existing literature on EROI of nuclear energy should be performed since it is not the purpose of this paper. Such appraisal should provide information especially about (i) what data are available; (ii) which protocols have been used; (iii) what types of problems can be found in the available data; as well as (iv) the main sources of uncertainty and ignorance.

The new EROI analysis will benefit from this critical appraisal avoiding as much as possible the analytical problems. This net energy analysis will especially have to take into account the correct and most significant production processes in relation to the different available nuclear technologies. Although empirical data will be limited or even not available, it would be wise to also analyze the EROI of future nuclear technologies that are still under development, such as breeder reactors, thorium powered nuclear reactors, potential fusion reactors and even increasingly popular small modular nuclear reactors. The EROI analysis will then have to make the right assumptions in terms of energetics for each production process using as much as possible empirical data making sure that they are suitable to the analysis and cross-referencing them with other available data.

This net energy analysis will be useful to give a technical explanation to different forms of the nuclear energy chain and to make it possible to represent the metabolic pattern of society in quantitative terms. Moreover, the EROI analysis will make it possible to conduct a basic MuSIASEM analysis on the viability of nuclear energy as a Primary Energy Source.

4.2. Step 2. Development of an integrated assessment methodology of the performance of nuclear energy in relation to the metabolic pattern of modern society

After determining the potential supply of net energy and the relative requirement of inputs (on the biophysical side) it becomes possible to consider the non-equivalent costs and negative impacts of this net supply. In this second phase, the biophysical analysis of production of nuclear energy will be translated into an integrated assessment by considering different criteria of performance. This implies considering all relevant factors required to give meaning to the semantics. This can be obtained by explaining: (i) how the system functions from the inside; and (ii) its interface with the context. As a result of this analysis, it becomes possible to check the congruence between: (1) the assessment done according to the technical information gathered in the first step; and (2) the problem structuring of the public debate over nuclear energy in the society. Are we sure that the current public debate on nuclear energy is based on a right perception of its pros and cons? What are the criteria of performance the most relevant to the general public?

Such an integrated assessment of the performance of nuclear energy in relation to the metabolic pattern of modern society is made possible by using the Multi-Scale Integrated Assessment of Societal and Ecosystem Metabolism (MuSIASEM) scheme, developed by Giampietro and Mayumi [Giampietro et al., 2008], as a general framework. Indeed, the MuSIASEM could be an effective tool for this discussion thanks to its ability to represent criteria of performance of a socio-economic system in relation to different factors and different non-equivalent domains. The MuSIASEM is also a unique and advanced semantically open analytical tool that can link the system to the whole societal structure and give meaning to it.

In practical terms, here are some tentative ideas on how to adapt the MuSIASEM scheme to a viability assessment of nuclear energy. Readers willing to familiarize themselves with the rationale and theory involved with MuSIASEM will find an outline in Giampietro et al. [2008]. According to the definition of the authors, "the MuSIASEM scheme is an operationalization of Georgescu-Roegen's bioeconomic approach to the economic process that explicitly addresses biophysical feasibility and constraints" [Giampietro et al, 2008]. In other words, the MuSIASEM scheme is an analytical tool especially designed to study an economic process (such as the nuclear energy production process) in relation to its external constraints and its internal constraints. A system of (quantitative) accounting within the MuSIASEM scheme is defined using a set of different concepts explained as follows.

4.2.1. Parameters

Feasibility and desirability can be analyzed considering different parameters (or factors) depending on the metabolic pattern of the economic process in question, i.e. the exploitation of the Primary Energy Source. Each parameter (being economic, biophysical, social, etc.) is introduced as either a flow or a fund of the economic system into the flow-fund representation of MuSIASEM. As far as the feasibility and desirability assessment of the nuclear energy production process, we could identify the following parameters (but not limited to): (i) the Primary Energy Source (i.e. thermal nuclear energy); (ii) the Energy Carrier (i.e. electricity); (iii) the human time (working hours); (iv) the financial capital invested; (v) the quality of natural resources (natural enrichment of uranium ore); and (vi) the generated wastes (nuclear by-products, greenhouse gases, etc.).

The first two parameters come from the net energy analysis performed in step 1, while the other ones would have to be quantitatively evaluated at the time of the integrated assessment (step 3). Those factors need to be selected according to criteria of performance that are the most relevant to the general public, which will give the integrated assessment its usefulness and pertinence. Therefore, the definition of such parameters is an essential step of a discussion about the potentiality of nuclear energy, and thus would require particular attention.

Once the key parameters (called extensive variables under the MuSIASEM scheme) are identified, they will be cross-referenced so that they can be expressed in terms of flow ratios, fund ratios or flow/fund ratios (called intensive variables). Those intensive variables will give an explanation of how the system functions from the inside. However, they will not be able to give information about its interface with the context which is essential to get a full picture of the economic system in relation to the rest of society.

4.2.2. Scales

In order to get a full understanding of the interface between the economic system and its context, it is necessary to look at the big picture of the technology in question, i.e. its role within the whole society, rather than focusing only on its direct economic pattern. This is made possible by considering different scales (or levels) when studying the viability of an energy source. The MuSIASEM scheme is especially a tool that allows to consider as many scales as necessary to perform the viability assessment. It links together factors from different hierarchical levels through a bottom-up analytical process from the level of the energy production process to the level of the society. In addition to make comparisons between the values of parameters referring to different hierarchical levels, the MuSIASEM approach can also be used to compare parameters being at the same hierarchical level but belonging to different places [Giampietro et al., 2008]. This will be useful when assessing the potentiality of nuclear energy or of its production processes, as discussed below, that can be located in different countries or regions.

In practical terms, some of the above cited factors can be evaluated at different hierarchical levels so that the flow-fund representation of the MuSIASEM scheme can be set at the interface between two successive levels. For example the human time factor can correspond either to the total time of human activity in the society (level n), the working hours of the paid work sector (level n-1), as well as the working hours of the energy and mining sector (level n-2). As far as the discussion about the viability of nuclear energy, it would be wise to perform the integrated assessment starting from level n-4 which corresponds to the level of the different production processes (mining; uranium enrichment; nuclear power plant operation; waste management; etc.) that take part of the nuclear energy sector (level n-3). This seems to be useful since (1) one production process can be used in different nuclear energy conversion technologies which viability can be assessed using mutual production process results; and (2) it becomes possible to identify which production process within a given technology is the weak link according to the criteria of performance we look at. In other words, performing an integrated assessment of nuclear energy down to level n-4 allows us to assess how the system functions inside in its deepest manner. In other words, it would not be realistic to assess the viability of the nuclear energy sector without looking at the level of its production processes.

4.2.3. Criteria of performance

As discussed above, the criteria of performance will have to be selected so that they are the most relevant to the general public since the purpose of the analysis is to support the public debate about alternative energy sources. Going further, this is especially the role of the society as a whole to decide which criteria are relevant and which ones are not. For this preliminary study, it is possible to identify some criteria of performance related to nuclear energy with no intention any of giving more importance to some criteria rather than to others. Such criteria of performance of the nuclear energy production economic system could be: (i) economical interest; (ii) amount of energy supplied; (iii) availability of the nuclear plants; (iv) safety of the nuclear operation; (v) non-proliferation of the nuclear fuel; (vi) radiation level of the nuclear wastes; (vii) nuclear fuel availability; (viii) environmental impacts; (ix) social impacts; etc. Note that there is no mention here about how to express those criteria of performance in quantitative terms, and that one criterion of performance can be expressed using several quantitative variables.

After defining the parameters, scales, and criteria of performance of nuclear energy as discussed above we will come up with an analytical tool that is ready to use to actually perform the integrated assessment.

4.3. Step 3. Carrying out an integrated assessment of the potentiality of nuclear energy

Both the feasibility and the desirability of the nuclear option as an alternative energy source will be assessed using the findings gathered in the first two steps. While doing so, we will use two key conceptual tools that are related to the MuSIASEM scheme: (i) the mosaic effects, and (ii) the impredicative loop analysis [Giampietro et al., 2008].

Quoting the authors, “the combination of extensive variables and intensive variables gives us redundant but useful information to increase the robustness of the analysis”, which corresponds to the ‘mosaic effects across levels’. Later they add that “the generation of redundant information is also useful to see whether or not the data set coming from various sources are compatible with each other, or whether or not the assumptions about future scenarios are plausible”. This tool will be certainly of help to study the viability of nuclear energy given the discrepancy of results in existing studies and the need for cross-referencing empirical data as discussed above.

‘Impredicative’ is an adjective that qualifies a situation where “what is defined participates in its own definition” [Kleene, 1952; in Giampietro et al., 2008]. This corresponds to what we discussed before through the chicken-egg problem of any viability assessment. “Impredicativity is considered as a nuisance in scientific reductionism since it makes it impossible to establish a linear causation, which is a typical goal of traditional scientific activity” [Giampietro et al., 2008]. Usually, this problem is resolved in scientific analysis by choosing one particular linear causation which will be validated empirically. However, such an approach is not possible with a metabolic system operating on different levels [Giampietro et al., 2008]. As a matter of fact, “impredicative loop analysis is an attempt to deal with this problem within the MuSIASEM scheme” [Giampietro et al., 2008] by representing the reciprocal constraints between the different parameters and scales.

Finally, using these two key conceptual tools within MuSIASEM allows us to perform the integrated assessment discussed so far accounting for the non-linearity that exists with any sustainability analysis.

5. CONCLUSION AND RESULTS

5.1. Findings

The three main findings of this tentative exploration of the viability of the nuclear option as an alternative energy source are that (i) such a study is necessary; (ii) it has not been performed to date; and (iii) it is made possible using the MuSIASEM scheme described above.

In particular, we discussed the fact that the nuclear option intends to be a good candidate for the future of energy given the current economic and environmental circumstances. However, we pointed out the discrepancies between results of existing studies about nuclear energy which means that there is no consensus about its potentiality yet. Especially the discrepancies have been identified as coming from analytical problems and/or conceptual problems in existing studies.

Later, we defined the viability of an economic system as being both its biophysical feasibility and its desirability in relation to the metabolic pattern of modern society. Then it has been explained that the purpose of such a viability assessment is to support the public debate about alternative energy sources rather than answering alone the question whether or not nuclear energy should play a role in the future of energy, since the final decision about the nuclear energy deployment remains the duty of the society as a whole.

Lastly, we tentatively explored how to engage a serious discussion about nuclear energy. Three steps have been identified in order to perform the viability assessment: (i) performing a critical appraisal of the existing net energy analyses about nuclear energy as well as performing our own EROI analysis; (ii) developing an integrated methodology of assessment adapted to nuclear energy; and (iii) carrying out the integrated assessment of the potentiality of nuclear energy using the findings gathered in the first two steps.

5.2. Conclusion

What is at stake with the future of energy clearly is whether or not human will be capable of co-evolving with the environment while meeting its energy *needs*. The term co-evolution [Kallis, 2007] means a process where we are able to change our identity if necessary rather than always trying to fix the outside world. This entails switching from a steady-state representation of the metabolic pattern of society to an evolutionary view [Giampietro et al., 2008] which latter view is at play here when intending to perform such an integrated assessment of the viability of nuclear energy. Moreover, assessing the quality of alternative energy sources is considered as being a pre-requisite toward co-evolution between modern society and the environment.

Finally, as we intended in this paper to pave the way for a serious discussion about the future of the nuclear option as an alternative energy source, the reader is warmly invited to provide critiques and advices based on these tentative ideas given that (1) particular attention must be paid to the definition of such an integrated assessment; and (2) this topic is considered as one of the most urgent energy issues.

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