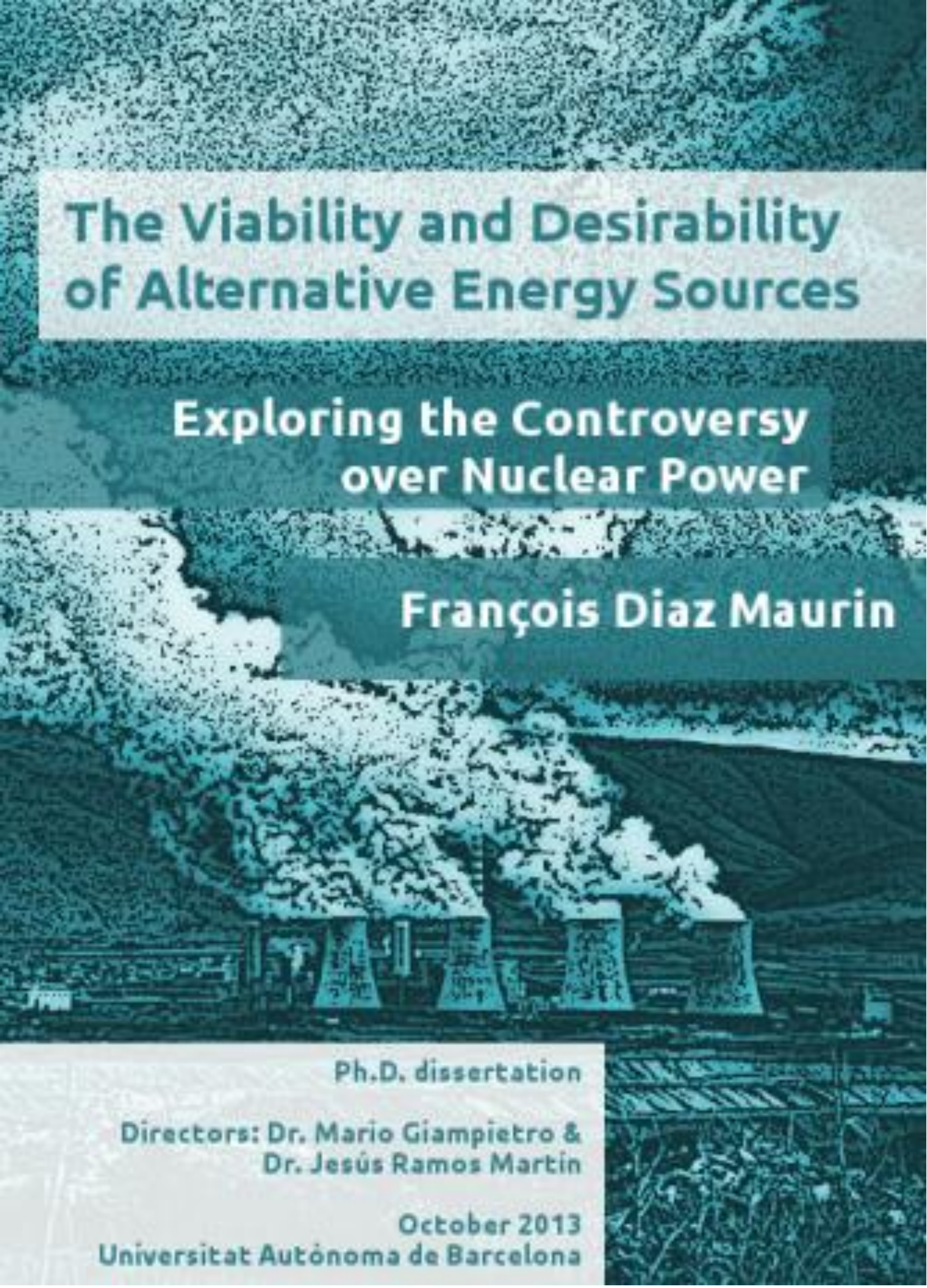

The Viability and Desirability of Alternative Energy Sources

Exploring the Controversy over Nuclear Power

François Diaz Maurin

Ph.D. dissertation

Directors: Dr. Mario Giampietro &
Dr. Jesús Ramos Martín

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About the Integrated Assessment research group at ICTA-UAB

The Integrated Assessment: Sociology, Technology and the Environment (IASTE) research group is hosted by the Institute of Environmental Science and Technology (ICTA) of the Universitat Autònoma de Barcelona (UAB) and supported by the SGR program of the Catalan Government.

The IASTE research group is capable of delivering scientific output strongly needed for dealing with the current sustainability predicament: an alternative narrative and quantitative representation of the interaction socio-economic systems/nature.

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This doctoral dissertation is dedicated to
the memory of José-Francisco Diaz Maurin (1951–2002)
from whom I got the restless curiosity of a "touche-à-tout"
and the endless heart of a passionate soul.

Abstract

This doctoral dissertation provides an alternative take on two related topics: the energetics of human societies (the approach), and the use of nuclear energy to make electricity (the issue). First, in relation with theoretical aspects, it provides alternative procedures based on a new formulation of energetics to generate effective analysis of the energetics of human societies. Second, in relation with practical application, it performs an integrated assessment of nuclear power based on an alternative representation of the "nuclear energy system" aimed at guaranteeing the quality of the assessment of nuclear power both on descriptive and normative sides.

By doing so, the present work intends to improve the quality of the scientific discussions over energy-supply issues, and at the same time, to better understand the systemic problems associated with the large-scale deployment of nuclear power.

In recent years the revived interest from the scientific community over energy-supply issues was turned into a desperate search for alternative energy sources. Yet, performing the critical appraisal of the potentiality of alternative energy sources to power modern societies requires first handling the systemic problems of conventional energy analysis once and for all.

First, dealing with the energy transformations of living systems such as human societies requires adopting a 'complex systems thinking' approach due to the unavoidable co-existence of multiple relevant dimensions and multiple relevant scales. This "technical incommensurability" on the descriptive side implies abandoning the use of the excessive simplifications of reductionism consisting in protocols generating numbers based on the adoption of one scale and one dimension at the time.

Second, when deliberating over sustainability issues there is an obvious existence of different social actors – different potential story tellers – expressing non-equivalent but legitimate perceptions of the same issue based on their values, beliefs and goals. This problem of "social incommensurability" on the normative side is particularly evident when considering the case of nuclear power in the discussion over alternative energy sources. In fact, one easily finds contrasting – and even opposite – perceptions over the viability and desirability of this technology, a fact which is at the origin of its systemic controversy. This situation reflects the impossibility to generate a shared perception between social actors over the use of this technology as a viable and desirable alternative energy source. The case of nuclear power provides a very good example why alternative energy sources cannot be taken as desirable and viable "by default". In fact, this dissertation indicates that we can only deliberate about the viability and desirability of alternative energy sources by means of "participatory integrated assessment", which forces revisiting the role of the scientist when using science for governance

Keywords:

Alternative energy sources, Complex energetics, Energy accounting, Energy-supply issues, Interdisciplinary science, Multi-scale integrated assessment, Nuclear power, Power-supply systems, Science for governance, Societal metabolism, Sustainability assessment

Résumé

Cette thèse doctorale propose une vision alternative sur deux sujets connexes: l’énergétique des sociétés humaines (l’approche), et l’utilisation de l’énergie nucléaire pour la production d’électricité (la question). Tout d'abord, en ce qui concerne les aspects théoriques, elle propose des procédures alternatives basées sur une nouvelle formulation de l’énergétique pour produire une analyse efficace de l’énergétique des sociétés humaines. Ensuite, en ce qui concerne l’application pratique, elle effectue une évaluation intégrée de l’énergie nucléaire basée sur une représentation alternative du « système de l’énergie nucléaire » qui vise à garantir la qualité de l’évaluation de l’énergie nucléaire à la fois sur les aspects descriptifs et normatifs.

Ce faisant, le présent travail entend améliorer la qualité des débats scientifiques sur les questions d’alimentation en énergie, et en même temps, mieux comprendre les problèmes systémiques liés au déploiement à grande échelle de l'énergie nucléaire.

Au cours des dernières années, le regain d’intérêt de la communauté scientifique sur les questions d’alimentation en énergie s’est traduit par une quête désespérée aux sources d'énergie alternatives. Pourtant, effectuer une évaluation critique de la potentialité des sources d’énergie alternatives pour alimenter les sociétés modernes exige de résoudre une fois pour toutes les problèmes systémiques des analyses énergétiques conventionnelles.

Tout d’abord, traiter des transformations énergétiques des systèmes vivants tels que les sociétés humaines nécessite l’adoption d’une approche de « pensée complexe des systèmes » en raison de la coexistence inévitable de multiples dimensions pertinentes et de multiples échelles pertinentes. Cette « incommensurabilité technique » du côté descriptif requière l’abandon de l’utilisation du réductionnisme aux simplifications excessives consistant en des protocoles générant des chiffres fondés sur l’adoption d'une seule échelle et dimension à la fois.

Ensuite, lors des délibérations sur les problématiques de soutenabilité il y a une existence évidente de différents acteurs sociaux – et autant de narrateurs potentiels – exprimant des perceptions non équivalentes, mais légitimes, au sujet d’une même problématique en fonction de leurs valeurs, croyances et objectifs. Ce problème d' « incommensurabilité sociale » du côté normatif est particulièrement évident lorsque l'on considère le cas de l'énergie nucléaire dans le débat sur les sources d'énergie alternatives. On observe en effet facilement des perceptions contrastées – voire même opposées – quant à la viabilité et à la désirabilité de cette technologie, ce qui est à l'origine de sa controverse systémique. Cette situation reflète l'impossibilité de générer une perception partagée entre les acteurs sociaux sur l'utilisation de cette technologie comme une source d'énergie alternative viable et désirable. Le cas de l'énergie nucléaire constitue un très bon exemple expliquant pourquoi les sources d'énergie alternatives ne peuvent pas être considérées comme viable et désirable « par défaut ». En effet, cette thèse montre que nous ne pouvons délibérer sur la viabilité et la désirabilité des sources d'énergie alternatives qu'au moyen d' « évaluation intégrée participative », ce qui suppose de revoir le rôle du scientifique dans l'utilisation de la science pour la gouvernance.

Mots clés :

Comptabilité de l'énergie, Energétique complexe, Energie nucléaire, Evaluation intégrée multi-échelle, Evaluation de la soutenabilité, Métabolisme des sociétés, Problématiques d'approvisionnement en énergie, Science interdisciplinaire, Science pour la gouvernance, Sources d'énergie alternatives, Systèmes de production d'électricité

Resumen

Esta tesis doctoral proporciona un giro alternativo en dos temas relacionados: la energética de las sociedades humanas (el enfoque), y el uso de la energía nuclear para producir electricidad (el tema). En primer lugar, en relación a los aspectos teóricos, proporciona procedimientos alternativos basados en una nueva formulación de la energética para generar un análisis eficaz de la energética de las sociedades humanas. En segundo lugar, en relación con la aplicación práctica, se realiza una evaluación integrada de la energía nuclear sobre la base de una representación alternativa del "sistema de la energía nuclear" con el objetivo de garantizar la calidad de la evaluación de la energía nuclear, tanto en el lado descriptivo como en el lado normativo.

De este modo, el presente trabajo tiene la intención de mejorar la calidad de las discusiones científicas sobre los problemas de suministro de energía, y al mismo tiempo, comprender mejor los problemas sistémicos asociados con el uso a gran escala de la energía nuclear.

En los últimos años, el renovado interés de la comunidad científica sobre los problemas de suministro de energía se convierte en una desesperada búsqueda de fuentes alternativas de energía. Sin embargo, la realización de la valoración crítica del potencial de las fuentes de energía alternativas para alimentar a las sociedades modernas requiere gestionar los problemas sistémicos del análisis convencional de la energía, de una vez por todas.

En primer lugar, al confrontarse a las transformaciones de la energía de los sistemas vivos, como las sociedades humanas, requiere la adopción de un enfoque de "pensamiento complejo de los sistemas" debido a la inevitable coexistencia de múltiples dimensiones relevantes y múltiples escalas pertinentes. Esta “inconmensurabilidad técnica” en la parte descriptiva implica el abandono del uso de las simplificaciones excesivas del reduccionismo que consisten en protocolos de generación de números basados en la adopción de solo una escala y una dimensión a la vez.

En segundo lugar, al deliberar sobre cuestiones de sostenibilidad hay una obvia existencia de diferentes actores sociales - diferentes narradores potenciales – que expresan sus opiniones no equivalentes, pero legítimas, sobre una misma cuestión basadas en sus valores, creencias y objetivos. Este problema de “inconmensurabilidad social” en la parte normativa es particularmente evidente cuando se considera el caso de la energía nuclear en la discusión sobre las fuentes alternativas de energía. De hecho, uno encuentra fácilmente percepciones diferentes - e incluso contrarias - sobre la viabilidad y conveniencia de esta tecnología, un hecho que está en el origen de su controversia sistémica. Esta situación refleja la imposibilidad de generar una percepción compartida entre los actores sociales sobre el uso de esta tecnología como una fuente de energía alternativa viable y deseable. El caso de la energía nuclear proporciona un muy buen ejemplo de por qué las fuentes de energía alternativas no pueden ser tomadas como algo viable y deseable "por defecto". De hecho, esta tesis indica que sólo podemos deliberar acerca de la viabilidad y conveniencia de fuentes alternativas de energía a través de una "evaluación integrada participativa", lo que obliga a revisar el papel de los científicos cuando se utiliza la ciencia para la gobernabilidad.

Palabras claves:

Ciencia interdisciplinaria, Ciencia para la gobernabilidad, Contabilidad de energía, Energética compleja, Energía nuclear, Evaluación integrada multi-escala, Evaluación de la sostenibilidad, Fuentes alternativas de energía, Metabolismo de las sociedades, Problemas de suministro de energía, Sistemas de suministro de electricidad

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Abbreviations

General

AEC	United States Atomic Energy Commission (the forerunner of the US Nuclear Regulatory Commission and the US Department of Energy nuclear program)
EPR	Evolutionary Power Reactor (the French flagship generation III+ reactor design by the reactor vendor AREVA)
FAO	Food and Agriculture Organization of the United Nations
GIS	geographic information system
IAEA	International Atomic Energy Agency
MuSIASEM	Multi-Scale Integrated Analysis of Societal and Ecological Metabolism
NRC	United States Nuclear Regulatory Commission
OECD	Organization for Economic Co-operation and Development

Compartments of the socioeconomic system

AG	agricultural sector
BM	building and manufacturing sectors
EM	energy and mining sectors
HH	household sector
PF	primary production sectors generating flows (AG and EM sectors) or simply primary flows
PS	primary and secondary production sectors or simply productive sectors
PW	paid work sector
SG	services and government sector

Fund elements

HA	human activity
PC	power capacity
PCD	power capacity dissipative
PCH	power capacity hypercyclic

PC-t	installed power capacity required for the consumption of thermal energy
PC-m	installed power capacity required for the consumption of mechanical energy
ML	managed land
THA	total human activity
TML	total managed land
TPC	total installed power capacity

Energy flows

EC	quantity of energy measured in joules of energy carriers
ET	energy throughput
ET-t	energy throughout in the form of thermal energy measured in joules of energy carriers
ET-m	energy throughout in the form of mechanical energy measured in joules of energy carriers
EU	end uses
GER	quantity of energy measured in joules of gross energy requirements
GSEC	gross supply of energy carriers
IMPEC	imports as EC (used as “end uses”)
IMPER	imports as GER (used for generating energy carriers)
NSEC	net supply of energy carriers
PES	primary energy sources (energy flows from physical gradients or imports measured in biophysical units)
REU	requirement of end uses
TET	total energy throughput (on a year basis)

Flow/fund ratios

EMD	exosomatic metabolic density (energy flow measured in joules of GER per hectare of land)
EMI	exosomatic metabolic intensity (energy flow measured in joules of GER per Watt of installed power capacity)
EMR	exosomatic metabolic rate (energy flow measured in joules of GER per hour of human activity)
SEH	strength of the exosomatic hypercycle
EROI	energy return on the investment

Preface

Before formally opening this doctoral dissertation, I would like to come back in non-scientific terms to the ins and outs of the making of this research work which has been organized around both *dedication* and *passion*.

Dedication as a student

> *The greatest pleasure in science comes from theories that derive the solution to some deep puzzle from a small set of simple principles in a surprising way.*
>
> —John Brockman (2013)[1]

From the perspective of my previous life as an Engineer in the nuclear industry, it was totally unexpected to start a Ph.D. program in Environmental Science and Technology and even less expected by adopting from such an interdisciplinary approach to science. This is the kind of spontaneous events – or emergent properties – that makes life surprising and thus more enjoyable.

Everything started at the 7th Biennial International Workshop on Advances in Energy Studies (BIWAES) co-organized by my directors, Mario Giampietro and Jesus Ramos-Martin, in October 2010 where I presented my "tentative ideas"[2] on how to deal with the viability and desirability of the "nuclear option" – using the terms of the Massachusetts Institute of Technology at the time[3] – whereas I was still officially employed

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[1] Brockman, J. (2013). This Explains Everything: 150 Deep, Beautiful, and Elegant Theories of How the World Works. HarperCollins.

[2] Diaz-Maurin, F. (2011). Tentative Ideas to Explore the Viability of the Nuclear Option. In: Ramos-Martin, J., Giampietro, M., Ulgiati, S. and Bukkens, S.G.F. (Eds.). Can We Break the Addiction to Fossil Energy? Proceedings of the 7th Biennial International Workshop, Advances in Energy Studies 2010, 19–21 October, 2010, Barcelona, Spain. Universitat Autònoma de Barcelona. pp. 579-589. The paper presented at the BIWAES conference is available at: http://www.societalmetabolism.org/aes2010/Proceeds/DIGITAL%20PROCEEDINGS_files/POSTERS/P_190_Francois_Diaz_Maurin_REV.pdf

[3] See http://web.mit.edu/nuclearpower/ (accessed 2 September 2013)

of this industry as not sure yet about the practical details of how I will sustain myself and my family by starting this Ph.D. program.

The feedbacks and encouragements received during that conference by those who would become the directors of this thesis, along with other researchers above mentioned in the acknowledgements, definitely convinced me that there may be something to do in that direction. Then, the nuclear reactor accidents at Fukushima in Japan happened in March 2011, that was the unexpected and unfortunate event which forced me to come out of my den.[4] As a citizen, I was very worried to be considered as “the expert” and asked to comment largely on an ongoing disaster for which I did not have more information – and not that much of knowledge – than the ones found in the news media. . . Then, as an aspirant scientist, this forced exposure was not the easiest thing to do when my previous conception of the making of a thesis was to give it a certain level of abnegation and distance as regard to the society. As fortunate for the progress of this thesis, as unfortunate for the sake of the public debate, the interest from the news media declined rapidly in the following months. In any case, a positive impact of this disaster has certainly been to refresh in the general public the concern about nuclear power which may add to the relevance and reception of this thesis.

Coming back to the making of this work, I must say that, when I started my PhD course, I was totally unaware of topics like sustainability science, interdisciplinary science and complex systems theory. As a layman, I had only some mere general knowledge about philosophy and science. At best, as a civil and mechanical Engineer, I acquired the necessary technical background but which was embedded within a Newtonian view of the world affected by over reductionism and a ‘normal’ approach to science. In short, I was novice to most of the epistemological troubles at the time of starting this research project, which may have helped, in the end, to go through all this new knowledge with a fresh mind. But, above all, this may be because the priority in my new endeavor was given to “making sense”, in contrast to the conventional “being true” approach that is the source of all troubles in modern science and for scientists. That is to say, after almost three years spent in my new intellectual life I now perceive – and hopefully I am able to represent in quantitative

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[4] The events of the 11 March 2011 at Fukushima revived fears and interests from the public opinion to the nuclear affairs, which led for me to a significant number of interviews in the Catalan news media, as well as to the organization by ICTA-UAB of a seminar on the nuclear accidents on 21 March 2011. A full list can be found in Appendix III.

terms – the world with a completely different mindset, that is, I believe, an irreversible process.

Passion as a disciple

> *The victory of the disciple is the glory of the master.*
>
> —Gerbert d'Aurillac, a.k.a. Pope Sylvester II (946–1003)[5]

This quote is used here to give a simple message: if this thesis is successful – i.e. if the general public will find it both relevant and useful in light of the forced energy transition that human societies are about to undertake – then, the merit must first and foremost go to Mario Giampietro, the *master* who has been behind most of the ideas developed in the present work. By saying this, it means that I fully accept my condition as a *disciple* of this very creative mind whereas, at the same time, I realize that the debt I owe him will never get paid back. In fact, there would never have been so much knowledge transferred and personal progress without the intellectual creativity and depth of my mentor's mind in the first place. He may owe himself part of his acquired knowledge to others[6], but that is another story. We are only nodes in a network of knowledge. Given this dilemma, I thus consider this debt as similar to the one that links fathers and children where the most important may reside in making a "good" use of the knowledge and wisdom received, eventually contribute in some ways to this knowledge, and finally teach it ourselves to the next generation of scientists – by adding our personal taste, of course!

At this stage, the teaching method of my mentor deserves consideration. In fact, Mario Giampietro applies a Zen (Ch'an) Buddhist method of teaching that can be summarized in Confucian (!) terms as:

> *If a student is not eager, I won't teach him;*
> *If he is not struggling with the truth, I won't reveal it to him.*

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[5] "*La victoire du disciple, c'est la gloire du maître*" (own translation from French)

[6] Mario Giampietro actually acknowledges himself those who inspired him in his first book: Giampietro, M. (2003). Multi-scale integrated analysis of agro-ecosystems. Boca Raton, FL: CRC Press, pp. xiii-xiv.

> *If I lift up one corner and he can't come back with the other three, I won't do it again.*
>
> —*The Analects*, Confucius[7]

I initially took – and still take – this wisdom very seriously. And I have to admit that it has been very effective so far given the level of new understanding achieved in such a short period of time. Indeed, in the past three years I have truly *become* someone else – Prigogine's proposal at work! This was materialized by a shift from *dedication* to *passion* throughout the progress of this research and of my understanding. The more I thought I knew, the less I actually did; which is the typical dilemma encountered by those embracing such a journey. Beyond the dedication of the student lies the passion of the disciple.

Becoming *a*[8] disciple of a personality like that of Mario Giampietro developed in me a belief in "complex energetics" that I do not reject. Indeed, no one can claim that rationality is the ultimate law that organizes human societies. For instance, the economic rationality is first and foremost a moral law[9], something that has been shown in quantitative terms by Mario Giampietro and co-workers themselves[10]. Moreover, by reading this thesis it should be clear that *beliefs* also affect the rationality over technology, and in particular nuclear power (see Chapter 6). Therefore, what Mario Giampietro showed me is that another narrative about how human societies are organized is possible! As a result, this belief – or enlightenment – was turned into imitation. Scars of that imitation appear clearly in my first scientific contributions[11], to the extent that my own language has been somewhat influenced by the literature of Mario Giampietro.

The phenomenon of imitation is well known from those studying the psychology of individuals. In his book, *The Laws of Imitation,* Gabriel Tarde (1890)[12] explains that

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[7] Opening quote in Giampietro, 2003.

[8] In fact, Jesus Ramos-Martin, the co-Director of this thesis, is another disciple of Mario Giampietro among many others. . .

[9] Dupuy, J.P. (2002). Pour un catastrophisme éclairé. Paris: Seuil, p. 34.

[10] For a deconstruction of the belief of economists in the perpetual growth see: Giampietro, M., Mayumi, K., & Sorman, A. H. (2011). The metabolic pattern of societies: where economists fall short. Routledge.

[11] For a full list of my recent publications and presentation, see Appendix III.

[12] Tarde (1890) Les lois de l'imitation.

one imitates what he admires, he sees fit and able to serve as his model. For him, the laws of imitation inherently govern the condition of the disciple. But he goes further by saying that the disciple shapes, in an original way by their mixture, the imitations selected from several sources. That is, imitation may be one strategy towards creativity and originality.

In fact, Tarde suggests that whereas the belief enables imitation, the *desire* makes it possible the *invention*. That is, in his condition as a disciple, one does not only express some belief, but also feel some desire as regard to his model. This is such a desire toward the revolutionary approach of "multi-scale integrated assessment of complex systems" that certainly defines best my relationship with this line of study for me. And the small touches of originality and creativity dotting this thesis here and there are hopefully the premises of future work.

With these two observations, I now realized that the journey which I have embraced over the past few years has filled many of my intellectual expectations and hopefully will find interest beyond. In one word, I probably found my Voie (Morin, 2013), which is a very lucky situation to live so early in one's intellectual and personal journey. Now, that I perceive the external world differently, let's hope that I will be able to carry on and keep representing it differently.

I believe that the same difference exists between dedication and passion as between prose and poesy. Sharing with the reader of this thesis at least a tiny fraction of the poesy about the interdisciplinary approach of complex energetics and multi-scale integrated assessment would already be a success from my perspective.

Now, that I made these few personal remarks, I hope the reader will enjoy going through the text of this dissertation as much as I had the pleasure of writing it.

Acknowledgments

I would like to thank, first of all, **Mario Giampietro**, from whom I learnt almost all the non-engineering knowledge developed in this thesis, and to whom I will always have a deep gratitude and respect for the knowledge he developed and brought to my eyes and those of the scientific community[13]. Second, I thank **Jesus Ramos-Martin** who has been the perfect complement to Mario Giampietro in guiding and supporting me throughout the thesis. In theoretical terms, as being himself the chief disciple of Mario Giampietro, his guidance was very important to immerge myself in the concepts I was not familiar with. His ability to translate and share about Mario Giampietro's work was key to my understanding. Especially, in the last stages of the making of this thesis his very relevant comments and suggestions certainly improved the quality of the present dissertation. In practical terms, Jesus has also been very present in relation to my integration in the academia and in the Catalan society.

I also would like to express my gratitude to the Integrated Assessment (IASTE) research group of the Universitat Autònoma de Barcelona (http://iaste-researchgroup.org/), and especially **Alevgul H. Sorman** (whose theoretical and empirical work inspired me since the very beginning and has been fundamental to the development of the herein proposed new procedures to energy accounting), **Zora Kovacic** (for our extended discussions and sharing of ideas about the governance of nuclear power which led to the writing of Chapter 6) and **Sandra Bukkens** (for being the "invisible hand" without whom this team could certainly not exist).

Special thanks should also go to **Cristina Madrid, Juan Cadillo** and **Tarik Serrano** (with whom I worked on the Nexus Assessment project (http://nexus-assessment.info/) commissioned by the FAO of the United Nations during which most of the theoretical developments were concretized and whose ideas and advices

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[13] A brief description of Mario Giampietro's teaching method and how it influenced the making of this thesis is provided in the Preface.

helped to make a major step towards this purpose), along with those already cited above.

I also warmly thank all other members of the IASTE research group, especially **Arnim, Gonzalo, Jampell, Pedro, Raul** and **Tiziano** (for the discussions and ideas we shared on various topics that certainly helped to provide the interdisciplinary background necessary to embrace this thesis), as well as the secretariat of the Institute of Environmental Science and Technology (ICTA) of the Universitat Autònoma de Barcelona, especially **Marta, Miguel, Sara, Silvia, Rafa, Yolanda** and **Jordina** (whose work in supporting the researchers and professors of ICTA certainly contributes to give this department its unconventional and prestigious identity).

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Last but not least, the making of this thesis have also been possible thanks to encouragements received from a handful of key senior researchers, and especially **Kozo Mayumi** (University of Tokushima), whose guidance, support and wisdom has been very beneficial throughout this research project; **Louis Lemkow** (Universitat Autònoma Barcelona), whose moral support has been very helpful to me, especially at the time when the Fukushima accidents started in March 2011; **Marcel Coderch Collell** (Advisory Council for the Sustainable Development of Catalonia) and **Charles A.S. Hall** (State University of New York College of Environmental Science and Forestry), who both encouraged me since the very beginning to pursue this research project when I presented my first paper on the subject entitled "tentative ideas" at the BIWAES workshop in Barcelona in October 2010; as well as **Michael Dittmar** (ETH Zurich) and **Francesco Spano** (Royal Holloway, University of London) who invited me to present the early results of this research project during a web-seminar organized by the conCERNed group at CERN in Geneva in April 2012.

Coming to the more intimate aspects that made possible this thesis, I want to first and foremost express my gratitude to **Harmonie**. She has been accompanying me over the last ten years being at once my true love, my confident, my best friend –

even sometimes being my best enemy! In particular, I thank her for her continuous patience and support throughout the past three years – a frenzied period in which we moved to another country where she was not even speaking the language, we eventually got married, she started her own small company, and we got our first child. . . – and especially for the even more frenetic period of the past five months of wrap-up of this dissertation during which I wrote one peer-reviewed article, two book chapters and two other unpublished chapters that were necessary to cover most of the ideas, concepts and applications performed during that period. Clearly, the expected arrival of this child has been the key driving force making possible the early completion of this research project. But all this would not have been possible without the trust from Harmonie in accepting to jump into this new life together. For this, I will ever remain deeply grateful to her.

Some of my friends and family members shall also be thanked for their large-spectrum influence on this thesis. In particular, I thank **Timur Kok** and **Romain Collaire**, who are two of the very few "old" friends to have accompanied me throughout my intellectual journey despite the distance and with whom I had countless discussions with in-depth and fruitful debates which certainly helped me to shape my mindset; **Sebastien Fleuriel** and **Jean-Pierre Schneider**, who have been very kind to guide and encourage me at the time I had to decide whether to jump or not into this new adventure; **Alexandre Diaz Maurin**, whose integrity has always been very inspiring to me and helped me not to lose grasp of the outside world; and **Rafael Diaz Maurin**, who has been very influential in the beginning of my (intellectual) life and helped me to develop my capacity of critical thinking and not to wait too much before trying to explore new things. What he probably does not know is the fact that he is the one who truly lit the wick few months before I decided to actually jump into this PhD program.

Last, but not least, I thank my former teachers and colleagues in France and in the U.S. from whom I learnt a lot and developed the technical background which is the first piece badly needed in the field of multi-scale integrated assessment – i.e. knowing how to guarantee *correctness*, beside the other necessary *robustness*, *relevance* and *usefulness* of applied interdisciplinary research. In particular, I thank **Michel Kahan** and **François Lebrun** (Setec TPI, Paris), **Edward E. Clayton** (Setec ALS, Lyon), **Dimitrios Antonopoulos** (AREVA Federal Services, Boston, MA) and **James Fitzpatrick** (AREVA NP, Boston, MA) for sharing with me their outstanding knowledge in their own technical fields.

All the persons mentioned above have been very influential to me, hence certainly contributed one way or the other to the quality of the work presented here. However, the views expressed in this dissertation as well as the possible errors or misconceptions shall remain my own responsibility.

Biographical sketch

François Diaz Maurin is an Engineer with expertise in large-scale infrastructure projects in the French and US nuclear industries. In the late 2010, he left the USA to join the Integrated Assessment research group (http://iaste-researchgroup.org/) of the Institute of Environmental Science and Technology (ICTA) at the Universitat Autònoma de Barcelona (UAB) and work with ICREA Research Professor Mario Giampietro on the application of MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) to energy supply issues. With this PhD thesis on assessing the viability and desirability of nuclear power by developing a new protocol to compare the quality of different alternative energy sources, François seeks to bring together his initial background in engineering and his newly acquired interdisciplinary knowledge – and identity! – on complex energetics and multi-scale integrated assessment.

François Diaz Maurin serves on the editorial board of *Frontiers in Energy Research* (Nature Publishing Group) as Review Editor of the specialty section “Energy Systems and Policy”.

For more information, see Appendix III.

Introduction

Issue definition and research objectives

The energy-supply issues

As surprising it may seem to today’s generations, humans have spent most of their history living in pre-industrial societies characterized by a "low carbon" economy. Even today, many subsistence societies are fully operating on renewable energy sources. Yet, modern societies are based on the massive use of fossil energy per capita, to the extent that it is sometimes referred to the “fossil-fuel civilization” characterizing such societies or to the geological period of the “Anthropocene” characterizing the large-scale appropriation by humans of the (energy) resources and processes provided by the Earth's ecosystems.

The source of all troubles comes from the fact that this pace of consumption that has been growing exponentially over the last century will not be sustained for a long period of time due to the implications of reaching the tipping point that makes impossible a further increase in the consumption of fossil energy sources. This point has been reached for coal in the 1920s in the U.S., for oil in today’s major exporting countries, and for natural gas it is expected in eastern Europe in the next few decades. Although the depletion of affordable fossil energy resources first maps onto a set of regional peaks of production, there is an unavoidable global trend towards a progressive depletion of those stock-flow energy resources. This is the rationale behind the desperate search for alternative energy sources which revived the interest of the scientific community over energy-supply issues.

Dealing with the issue of energy-supply requires dealing with the specific issue of the critical appraisal of the potentiality of alternative energy sources to power modern societies. This problem is particularly evident when considering the case of nuclear power proposed as an alternative energy source.

The controversy over nuclear power

When discussing of nuclear power in relation with other alternative energy sources, one easily finds contrasting – and even opposite – perceptions over its viability and desirability. Indeed, nuclear power can simultaneously appear as “clean”, “secure” and “cheap” to some, or “dirty”, “dangerous” and “not cost-effective” to others. Scientists are therefore facing a clear dilemma when dealing with the “nuclear predicament”: How to decide whether it is “good” or “bad” to have a lot of nuclear power plants? Who are the social actors whose values should be considered? What are the most useful perceptions associated with this issue? How to consider the preferences of future generations that in the next century will have to deal with the wastes?

When considering the normative side there is an obvious existence of different social actors – different potential story tellers – expressing non-equivalent but legitimate perceptions of the same issue based on their values, beliefs and goals. This “social incommensurability”[14] in relation to the definition of “desirability” implies that any decision inherently generates winners and losers. Nevertheless, this epistemological challenge does not imply that quantitative analyses are useless. In fact, no matter what the values held by social actors are, there are key pieces of information required on the descriptive side: What are the factors to consider for studying viability? What are the technical coefficients of possible options? What are the biophysical costs? What about uncertainty?

The controversy over nuclear power can therefore be attributed to the impossibility to generate a shared perception between social actors over the use of this technology as a viable and desirable alternative energy source[15]. Yet, since any quantification depends on a pre-analytical (arbitrary) choice of a narrative about what is feasible and desirable, more attention should be given to the quality of the process used to define the chosen perception of the problem.

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[14] Munda, G. (2008). Social multi-criteria evaluation for a sustainable economy. Springer.

[15] A good illustration of how the controversy over nuclear power affects the public debate can be looking at the “Nuclear power debate” article in Wikipedia which is among the top-10 most controversial articles in the French language edition. URL of the article: http://fr.wikipedia.org/wiki/ Débat_sur_l'énergie_nucléaire (accessed 10 Sep 2013). Source: Yasseri T., Spoerri A., Graham M., and Kertész J. (in press) The most controversial topics in Wikipedia: A multilingual and geographical analysis. In: Fichman P., Hara N., editors, Global Wikipedia: International and cross-cultural issues in online collaboration. Scarecrow Press. (To Be Published in 2014)

Participatory integrated assessment of energy systems

The controversy over nuclear power indicates that we can only deliberate about the *viability* and *desirability* of nuclear power by means of "participatory integrated assessment". This approach has two main theoretical implications:

(1) on the normative side – It requires mixing quantitative analysis to qualitative analysis.

This refers back to the need to change the focus of the discussion over sustainability from "truth" to "quality"[16] which requires revisiting the role of the scientist when using science for governance. Indeed, in this iterative process, natural scientists, generating the information space on the descriptive side have to work together with social scientists individuating valid narratives and relevant attributes of performance to be used for the formalization of the assessment. This process, however, requires new procedures and new rules developed to achieve such a result.

(2) on the descriptive side – It requires dealing with the unavoidable existence of multiple relevant scales to be considered in the quantitative analysis of complex systems, such as nuclear power when observed from the societal view.

Assessing the feasibility and viability of energy systems implies to check their quality in relation with characteristics at the higher scale of the society that, in return, implies dealing with complexity for which another set of rules is required. Indeed, when dealing with the quantitative assessments of complex processes operating across different scales – like energy systems – it becomes impossible to use the excessive simplifications of reductionism consisting in protocols generating numbers based on the adoption of one scale and one dimension at the time. The unavoidable co-existence of multiple relevant dimensions and multiple relevant scales in the discussion of sustainability implies that mono-scale analysis should not be used to define "the best course of action" when using science for governance.

Therefore, dealing with the energy transformations of living systems such as human societies requires adopting a 'complex systems thinking' approach in order to handle the systemic problems experienced so far in conventional energy analysis.

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[16] Funtowicz, S. O., & Ravetz, J. R. (1993). Science for the post-normal age. Futures 25: 735-755.

Research objectives

After having described the general issue of energy-supply within which this thesis is embedded and the specific problems involved when dealing with the energetics of human societies, it becomes possible to formulate the research objectives of the present thesis:

(1) in relation with theoretical aspects – developing alternative procedures based on a new formulation of energetics to generate effective analysis of the energetics of human societies;

(2) in relation with practical application – performing an integrated assessment of nuclear power based on an alternative representation of the "nuclear energy system" aimed at guaranteeing the quality of the assessment of nuclear power both on descriptive and normative sides.

Evolution of the thesis

When I started this research project in December 2010, the ambitious objective of trying to assess the viability of nuclear energy[17] clashed against the difficulty of answering in substantive terms to the above formulated research objectives. For this reason, starting with some technical discussion about the performance of nuclear power[18] due to my original technical background, I eventually developed an integrated approach to deal with this research question which implied unavoidable theoretical digressions so as to address practical issues encountered along the way.

Therefore, what originally was anticipated as a technical discussion ended up, almost three years later, becoming a theoretical discussion about the energetics and sustainability of human societies. While significant efforts have been made to maintain the original objective, it must be acknowledged that practice without theory rapidly fall short. But the reverse is also true: theory without practice is not necessarily relevant and useful. For this reason, the proposed structure of this thesis is articulated around these two crucial pieces of theory (the approach to energetics of human soci-

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[17] See my paper entitled "Tentative Ideas to Explore the Viability of the Nuclear Option" and presented at the BIWAES conference in October 2010 in the list of publications.

[18] See my technical reports in the list of publications.

eties) and practical application (the issue of nuclear power). As a matter of fact, the final structure of the text cannot reflect the evolution of the thesis where theory and empiricism were influencing each other in an impredicative way. This iterative process drove the making of the present work until the very last stages, something that hopefully provides robustness to the present work.

Contribution and limits of the present work

> *Practically, all works we usually call our own, represent only a few scoops of originality added on top of a mountain of knowledge received from others*
>
> – Nicholas Georgescu-Roegen (1971)[19]

In the field of interdisciplinary science and in the line of multi-scale integrated assessment in particular, one does not seek quantitative accuracy but relevance and usefulness over the semantic and formal processes used to generate scientific output. Yet, checking the relevance and usefulness of scientific output requires quality-control over the pre-analytical choices made in the analysis that can only be checked by external relevant actors which, in the case of the present thesis dealing with the energetics of human societies, corresponds to the society at large. For this reason, although strongly aimed at it, the thesis cannot answer in substantive terms whether it is relevant or – something that would be even more difficult – useful. However, in order to make possible the quality-control of the analysis, it is necessary to maintain transparency throughout the whole process of analysis. This transparency may be one criterion for the appraisal of the present work.

On the other hand, the process of performing so-called scientific analyses requires following a certain amount of *rules* – not to be confused with *laws*[20]. Rules help providing the correctness to the output which is a prime concern and that certainly is another relevant criterion of evaluation. However, as noted above and given the amount and variety of fields involved in the theoretical part – complex system theory, nuclear engineering, risk analysis, science for governance, epistemology, theoreti-

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[19] Georgescu-Roegen, N. (1971). The entropy law and the economic process. Cambridge, MA: Harvard University Press.

[20] Pattee, H. H. (1978). The complementarity principle in biological and social structures. Journal of Social and Biological Structures, 1(2), 191-200.

cal ecology, non-equilibrium thermodynamics . . . – as well as the effort of integration required to perform the integrated assessment of nuclear power – the present work cannot provide direct contributions to those fields, although it is true that most advances in science have been done outside their original fields of research, hence by outsiders or newcomers[21]. In any cases, if the present thesis is to be embedded within one specific scientific field, it must be understood as falling into the fields of "multi-scale integrated assessment" and "complex energetics", although it is very difficult to frame such a work under the realm of *normal* science.

Moreover, the scientific contribution of the present work may be divided into (i) some theoretical developments – as a set of alternative procedures to complex energetics of human societies; and (ii) an empirical application – as an integrated assessment of nuclear power. As such, it may therefore be checked against its correctness and robustness, but it would not stand – and is not aimed at – criteria such as exhaustiveness or quantitative accuracy.

Using Edgar Morin's[22] theory of action under complexity, this thesis is about navigating through a sea of uncertainty with some islands of certainty. That is, the contribution of the present work is about helping to extend the small island of the energetics of complex systems.

Specific outlines of the chapters

This thesis provides an alternative take on two related topics: the energetics of human societies (the approach), and the use of nuclear energy to make electricity (the issue). Part 1 provides a critical assessment of conventional methods of perception and representation used in energy analysis (Chapter 1) and in the discussions about nuclear power (Chapter 2). Then, Part 2 focuses on the development of alternative quantitative procedures to deal with the multi-scale integrated assessment of energy systems (Chapters 3 and 4); and Part 3 provides an application of those alternative procedures to the case of nuclear power in order to discuss its quality in a given context (Chapter 5) and its meaning in more general terms (Chapter 6).

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[21] Kuhn, T.S. (1962). The structure of scientific revolutions (3rd edn.). Chicago: University of Chicago Press.

[22] Morin, E. (1990). Introduction à la pensée complexe. Paris: ESF.

Part 1: Critical appraisal of conventional approaches

Chapter 1 provides an overview of innovative theoretical concepts that can be integrated to build a ‘complex energetics’ and of alternative analytical tools able to generate effective analysis of the energetics of complex systems. In fact, the adoption of a ‘complex systems thinking’ approach to the analysis of energy transformations in living systems – including human societies – makes it possible to handle the systemic problems experienced so far in conventional energy analysis. This was the rationale behind the emergence of a new formulation of energetics based on a transdisciplinary approach to science. The revolution in ‘complex energetics’ suggests that a more general ‘complexity revolution’ in sustainability sciences is possible.

Chapter 2 provides a critical assessment of the conventional perception and representation of nuclear power. In particular, it takes the case of how risks from nuclear power have been conventionally assessed, revealing some systemic misconceptions about the very notion of risk and explaining the systemic controversy of this technology. The chapter ends by proposing such an alternative representation of the “nuclear energy system” based on lessons from complex systems theory explored in Chapter 1. Adopting such an alternative view is crucial for assessing the viability and desirability of nuclear power as an alternative energy source.

Part 2: Alternative procedures in energy analysis

Chapter 3 provides the practical aspects to be addressed when applying the Multi-Scale Integrated Analysis of Societal and Ecosystem (MuSIASEM) approach to energy supply issues. In fact, building upon the toolkit of “complex energetics” presented in Chapter 1, MuSIASEM is an innovative approach to accounting able to integrate quantitative information generated by distinct types of conventional models based on different dimensions and scales of analysis that can be employed for diagnostic and simulation purposes. In particular, this chapter presents the procedures required to characterize the existing energetic metabolism of socio-economic systems (diagnostic tool), and the procedures required to perform a feasibility–viability–desirability check of proposed scenarios in relation to energy transitions (simulator tool).

Chapter 4 provides an innovative approach for the characterization and comparison of the performance of energy systems, that is a critical piece of the alternative procedures developed in Chapter 3. By using another grammar that focuses on the standard unit operations of energy systems, it provides an evaluation of the technical coefficients and production factors required by their flow and fund elements. In doing so, the chapter compares the performance of the nuclear energy system, as defined in Chapter 2, to the fossil-fueled system used for generating electricity. The observed low biophysical competitiveness of nuclear energy compared to fossil energy when used to make electricity may explain the difficulties faced by nuclear energy to gain interest from investors explored in Chapter 6.

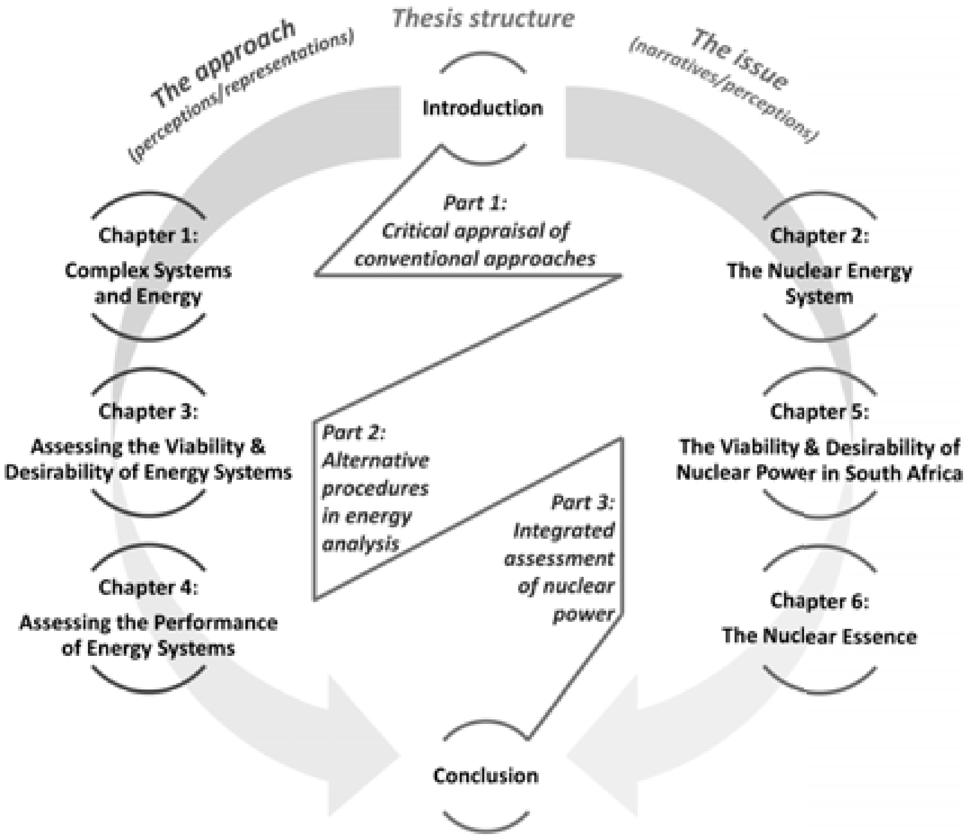
Part 3: Integrated assessment of nuclear power

Chapter 5 applies the new procedures to energy accounting developed in Chapters 3 and 4 to the case of South Africa that is currently undertaking a large-scale deployment of this technology in its mix of energy sources generating electricity. Indeed, the case of the South Africa's emerging economy provides a very good exercise for checking the feasibility, viability and desirability of nuclear power against external and internal constraints to the energetic metabolism of this country. The other purpose of this practical application is to check the robustness and usefulness of the new procedures to energy accounting developed in this thesis.

Chapter 6 is the concluding chapter of this thesis. Building upon the alternative representation of the nuclear energy system proposed in Chapter 2, it extends further the integrated assessment of nuclear power by analyzing its semiotic process that is especially useful in the discussion over its desirability as an alternative energy source. Indeed, by looking at the various narratives that have been at play throughout the history of nuclear power it is possible to identify key actors and drivers that constitute the *essence* of nuclear power, that is to say, its "why". This chapter attempts to act as a "red pill" capable of showing the painful truth of reality to the observer of nuclear power.

The present thesis is organized around three levels of reading that act as independent entry points to the various materials provided. The first level of reading corresponds to the linear structure of the thesis made of the three consecutive parts described above (Parts 1, 2 and 3). The second level corresponds to the approach of this thesis that focuses on the problem of perception and representation when dealing with complex energy systems (Chapters 1, 3 and 4). Finally, the third level of reading concerns the problem of perception and meaning encountered when dealing with nuclear power that is the underlying issue addressed throughout this thesis (Chapters 2, 5 and 6).

The following diagram summarizes the multi-level reading of the thesis.



Appendix I provides the technical coefficients required in the alternative procedures for the integrated characterization of the performance of the power-supply systems developed in Chapter 4.

Appendix II provides the entry points as well as the logical framework of the application of the alternative procedures to energy accounting developed in Part II used in the characterization of the energetic metabolism of South Africa performed in Chapter 5.

Appendix III provides the full curriculum of François Diaz Maurin.

List of publications

The present work is based on several publications, either already published, in press or accepted:

Diaz-Maurin, F. and Giampietro, M. (in press). Complex Systems and Energy. MS no. 01549. Online database on Earth Systems and Environmental Sciences. Elsevier.

Giampietro, M. and Diaz-Maurin, F. (in press) 'The Energy Grammar Toolkit'. In: Giampietro, M., Aspinall, R.J., Ramos-Martín, J. and Bukkens, S.G.F. (Eds). Resource Accounting for Sustainability: The Nexus between Energy, Food, Water and Land Use. Routledge series 'Explorations in Sustainability and Governance'. http://www.routledge.com/books/details/9780415720595/ (To Be Published 30th March 2014)

Diaz-Maurin, F. et al. (in press) 'South Africa's Emerging Economy'. In: Giampietro, M., Aspinall, R.J., Ramos-Martín, J. and Bukkens, S.G.F. (Eds). Resource Accounting for Sustainability: The Nexus between Energy, Food, Water and Land Use. Routledge series 'Explorations in Sustainability and Governance'. http://www.routledge.com/books/details/9780415720595/ (To Be Published 30th March 2014)

Diaz-Maurin, F. and Giampietro, M. (2013) A 'Grammar' for assessing the performance of power-supply systems: Comparing nuclear energy to fossil energy. Energy 49:162–177. DOI: 10.1016/j.energy.2012.11.014

In addition, other relevant publications have been made in the course of the Ph.D. thesis:

(i) Non peer-reviewed articles

Diaz-Maurin, F. (in press). Decreixement sostenible i Eficiència Energètica. Revista SAM, Vol. 21 Eficiència Energètica, Diputació de Barcelona, Servei de Medi Ambient. (Catalan) – Invited author.

Diaz-Maurin, F. (2012). L'incertitude comme limite à la maîtrise des risques. Interface 113: 20-21. ISSN 0985-3537. (French)

Diaz-Maurin, F. (2012). Fukushima : limites anthropologiques à la complexité et risque d'effondrement sociétal. Entropia 12: 99-108. ISSN 1954-2437. (French)

Diaz-Maurin, F. (2011). Sobre la viabilidad de la energía nuclear: Implicaciones de los accidentes de Fukushima-Daiichi. Ecología Política 41:106–111. July, 2011. (Spanish)

Diaz-Maurin, F. (2011). Fukushima: Consequences of Systemic Problems in Nuclear Plant Design. Economic & Political Weekly (Mumbai) 46(13):10–12. 26 March, 2011. URL: http://www.epw.in/commentary/fukushima-consequences-systemic-problems-nuclear-plant-design.html

Diaz-Maurin, F. (2011). Eléments de réflexion sur la question de l’énergie. Interface 109:45–47. ISSN 0985-3537. (French). URL: http://www.ingenieur-insa.fr/public/stockage/INTERFACE_109_WEB.pdf

(ii) Conference proceedings

Diaz-Maurin, F. (2011). Tentative Ideas to Explore the Viability of the Nuclear Option. In: Ramos-Martin, J., Giampietro, M., Ulgiati, S. and Bukkens, S.G.F. (Eds.). Can We Break the Addiction to Fossil Energy? Proceedings of the 7th Biennial International Workshop, Advances in Energy Studies 2010, 19–21 October, 2010, Barcelona, Spain. Universitat Autònoma de Barcelona. pp. 579-589. URL: http://www.societalmetabolism.org/aes2010/Proceeds/DIGITAL%20PROCEEDINGS_files/POSTERS/P_190_Francois_Diaz_Maurin_REV.pdf

(iii) Technical reports

Diaz-Maurin, F. (2012). Assessing the viability of power-supply systems: a tentative protocol, Reports on Environmental Sciences, Institut de Ciència i Tecnologia Ambientals (ICTA), Universitat Autònoma de Barcelona, 17 September 2012. URL: http://hdl.handle.net/2072/200847

Diaz-Maurin, F. (2012). Biophysical requirements of power-supply systems: nuclear energy and fossil energy, Reports on Environmental Sciences, Institut de Ciència i Tecnologia Ambientals (ICTA), Universitat Autònoma de Barcelona, 31 January 2012. URL: http://hdl.handle.net/2072/179690

Diaz-Maurin, F. (2011). The Problem of the Competitiveness of Nuclear Energy: A Biophysical Explanation. Working Papers on Environmental Sciences, Institut de Ciència i Tecnologia Ambientals (ICTA), Universitat Autònoma de Barcelona, 15 September 2011. URL: http://hdl.handle.net/2072/169668

(iv) Book reviews

Diaz-Maurin, F. (2013). Review of "Towards an Integrated Paradigm in Heterodox Economics: Alternative Approaches to the Current Eco-social Crises", Julien-François Gerber, Rolf Steppacher (Eds.). Palgrave Macmillan, London (2012). Ecological Economics 88c: 178–179. doi: 10.1016/j.ecolecon.2013.01.002

Part 1

Critical appraisal of conventional approaches

Chapter 1
Complex systems and energy*

This chapter provides an overview of innovative theoretical concepts that can be integrated to build a ‘complex energetics’ and alternative analytical tools able to generate effective analysis of the energetics of complex systems. In fact, the adoption of a ‘complex systems thinking’ approach to the analysis of energy transformations in living systems – including human societies – makes it possible to handle the systemic problems experienced so far in conventional energy analysis. This was the rationale behind the emergence of a new formulation of energetics based on a transdisciplinary approach to science. The revolution in ‘complex energetics’ suggests that a more general ‘complexity revolution’ in sustainability sciences is possible.

1.1 Introduction

This overview of the interdisciplinary field of ‘energetics of complex systems’ is used to give a very simple message: human societies will face dramatic changes in their energetic pattern in the next decades and for this reason it is crucial to improve our ability to carry out an effective energy analysis. The oil crises of the 1970s and 1980s have given an early warning to the community of practitioners working in the field of energy analysis and to the scientific community in general, about the dangerous dependency on fossil energy of modern civilization. However, the rebound of economic growth following these energy crises gave a temporary relief to the world economy. The prosperous economic growth in the 1990s was used to dismiss early concerns about sustainability. So the emergence of a new scientific field looking at the biophysical roots of the economic process – e.g. a systemic analysis of energy transfor-

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[*] This chapter has been edited as an overview article published as: Diaz-Maurin, F. and Giampietro, M. (in press). Complex Systems and Energy. MS no. 01549. Online database on Earth Systems and Environmental Sciences. Elsevier.

mations describing the interaction of human societies with the environment – was first stopped and then abandoned.

The remaining sections of this paper are organized as follows:

* Section 1.2 provides an historical discussion about the early attempts to deal with the energy transformations of human societies. This section concludes showing that dealing with the energy transformations of living systems such as human societies requires adopting a 'complex systems thinking' approach;

* Section 1.3 explains that a 'complex systems' reading of the energy transformations of living systems requires a new formulation of energetics capable of handling the systemic problems found in energy analysis. More specifically this section: (1) introduces a few concepts of complexity in science and in energy analysis; (2) provides a critical assessment of the systemic problems founds in conventional energy analysis based on complexity theory; and (3) discusses theoretical and practical implications of these two sections for the field of energy analysis;

* Section 1.4 presents the 'complex' formulation of energetics based on a transdisciplinary approach to science. In particular, it provides (1) an overview of innovative theoretical concepts that can be integrated to build a 'complex energetics'; (2) an overview of alternative analytical tools making it possible to generate effective analysis of the energetics of complex systems; and (3) a summary of the 'multi-scale integrated assessment' toolkit that can be used for a 'complex energetics';

* Section 1.5 suggests that a revolution in 'complex energetics' may pave the way to a more general 'complexity revolution' in sustainability sciences since the solutions adopted for dealing with the epistemological predicaments of multiple scales in 'complex energetics' can be used also to cope with the epistemological problems faced in economics.

1.2 The troublesome birth of energetics

'Energetics' emerged from the first revolution in classic science posed by the development of classical (equilibrium) thermodynamics in the 19th century. The field of energetics later lived its own first revolution with the development of non-equilibrium thermodynamics in the 1960s (the second revolution in classic science). However, those two scientific revolutions have not been sufficient for 'energetics' to be considered as an actual scientific field by the scientific community and society at large. Here the historical foundations of energetics are explored making possible to discuss the reasons of such a failure.

1.2.1 The 'classical formulation' of energetics

The classical (equilibrium) formulation of energetics intrinsically is linked to the emergence of thermodynamics in the middle of the 19th century which led to the first revolution in quantitative science. Thermodynamics was developed by engineers outside the domain of traditional physics, when developing the steam engines that would make the industrial revolution happen. In particular, a group of engineers from Scotland including Kelvin, Joules, Rankine and Maxwell focused on thermodynamic cycles building upon the first experiments made in France by Carnot and Clapeyron. Retrospectively thermodynamics started with practical applications which were later on turned into theoretical discussions. The term "energetic" was coined by Rankine himself. Energetics that was originally defined as a systemic study of transformations among different energy forms was rapidly generalized as "the science of energy". However such general claims about its scope clashed against the weakness of its formulation in scientific terms. Certainly, this mismatch between huge claims and little theoretical understanding resulted into a scientific fiasco of this emergent field. This implied the movement from a "science of energy" – the grand claim of energetics – to "thermodynamics" – a more restricted rigorous analysis of transformations of thermal and mechanical energy under controlled conditions. More specifically:

(1) in relation to its 'idealistic' formulation – The rigorous quantitative formulation of thermodynamic laws by Boltzmann, Planck, and Gibbs was made at the expense of an irremediable simplification over the representation of the external world. In particular, by assuming that energy transformations can be measured and controlled with the required accuracy, in order to describe them usefully with thermodynamic equations we have to accept two quite heavy assumptions: (i) all the energy forms relevant for the observed phenomena can be well defined and measured; and (ii) system attributes are not changing in time over the duration of analysis. These two assumptions have been proven impossible by the later developments of thermodynamics (this is what the second principle of the thermodynamics is about!) as theoretically formalized later on. Put in another way, the 'classical formulation' of thermodynamics formalized in thermodynamic laws was obtained by reducing the external world

to a mechanical system with boundaries assumed to be perfectly known both in space and time. As a matter of fact, "ideal cycles" were considered as the reference in the engineering applications of thermodynamics despite the fact that they do not exist (and they cannot exist!) in practice.

(2) in relation to its 'unrealistic' scope – Outside the technical development of thermodynamics, energetics was seen by its pioneers as a science of energy capable of providing an alternative to the leading mechanical (Newtonian) view of the external world – e.g. Ostwald, 1907; 1911. Going one step further on this idea, Ostwald's intent with his "energetic imperative" was to make energetics a discipline applied to many domains including the functioning of human societies. Unsurprisingly, such statements over the scope of energetics very rich on the semantic side clashed against its reductionist formulation in technical applications – the development of thermal engines. The new born field of energetics was unable to deal with socio-economic systems for the good reason that it was entering into the category of living systems governed by laws that were still unknown at that time (partially addressed later on with the development of non-equilibrium thermodynamics). According to the very general principles of thermodynamics, living systems were all "special" and therefore it was impossible to describe their relevant features with the narratives of thermodynamics. As a matter of fact, according to the narratives of equilibrium thermodynamics the most probable outcome of energy transformations is the destruction of all gradients, "the heat death of the universe". In fact, life emerges from a phenomenon called 'symmetry breaking' in physics (Anderson, 1972), hence far away from equilibrium. Something not directly related with the ideal cycles imagined in classical thermodynamics. Moreover, 'open self-organizing living systems' started to be characterized by biologists in the late 1970s outside the field of energetics (see sect. 1.4.1). For these reasons the first formulation of energetics was unable to successfully address problems typical of living systems that were not properly understood in this field.

1.2.2 The 'non-equilibrium formulation' of energetics

The second formulation of energetics emerged from the development of non-equilibrium thermodynamics in the early 1960s (the second revolution in classic science). Contrary to classical thermodynamics that was developed through engineering applications, non-equilibrium thermodynamics resulted first from theoretical discussions associated with the characterization of 'becoming systems' (Prigogine, 1961;

see also sect. 1.4.1) and the famous question of Schrödinger (1967) – “what is life?”. Non-equilibrium thermodynamics was therefore seemingly able to deal with the energetics of living systems. However, although the ‘non-equilibrium’ formulation has been very beneficial to the field of energetics in semantic terms, it failed to provide a practical operationalization of those new concepts (an example of how to deal in practice with the energetics using a complex systems approach is presented in sect. 1.4). Indeed the application of energetics to socio-economic systems was not accompanied with proper methods capable of addressing the “expected” characteristics of complex self-organizing systems: organization across multi-scale, unavoidable openness determining fuzzy boundary definition, impredicativity (chicken-egg paradoxes). As a result, even after the emergence of non-equilibrium thermodynamics, energy analysis was still unable to provide sound quantitative assessments in response to the first energy supply crises of the 1970s and 1980s. In spite of a surge in the interest in this field at the time both the concepts and the protocols proposed did not delivered the expected results (Giampietro et al., 2012). This fact, certainly explains the further delusion of the scientific community in relation to the field of energetics.

1.2.3 The need for a second revolution in energetics

Attempts to apply energy analysis to human systems have a long history. Pioneering work was done by, among others, Podolinsky, Jevons, Ostwald, Lotka, White, and Cottrel (for a review see chapter 6 of Giampietro and Mayumi, 2009). However, it was not until the 1970s that energy analysis became a fashionable scientific exercise, probably due to the oil crisis surging during that period. During the 1970s, energy input-output analysis was widely applied to farming systems and national economies and was applied more generally to describe the interaction of humans with their environment. Odum (1971; 1983; 1996), Georgescu-Roegen (1966; 1975; 1976), and Pimentel (1980; Pimentel and Pimentel 1979), among others, developed theoretical approaches to generate systemic analysis of energy flows within ecological and socio-economic systems. At the IFIAS workshop of 1974, the term ‘energy analysis’ (as opposed to ‘energy accounting’) was officially coined. The second energy crisis during the 1980s was echoed by the appearance of a new wave of interesting work by biophysical researchers and a second elaboration of their own original work by the “old guard.” However, quite remarkably, after less than a decade or so, the interest in energy analysis declined outside the original circle. Indeed, even the scientists of this field soon realized that using energy as a numeraire to describe and analyze changes in the characteristics of agricultural and socio-economic systems proved to be more complicated than one had anticipated. Systemic problems in energy analysis (discussed in sect. 1.3.3) can only be addressed only after a second revolution in energetics based on complexity theory.

In relation to this point, the following quote from the lectures in energetics of Professor Parolini at the University of La Sapienza in Rome remarkably summarizes the new foundations which a second generation of 'energetic analysis' had to be based on in order to solve the epistemological impasse it was so far engaged into:

> *In relation to the unavoidable second revolution within energetics the following points should be kept in mind: energetics should deal with both qualitative and quantitative aspects of both scientific and technological solutions; applications must be interdisciplinary and address simultaneously several dimensions of analysis – i.e. referring to ecological systems, demographic processes, fresh water availability, material resources, interfacing the knowledge creation with biology, cosmology, metaphysics into a holistic vision of the world.*
>
> —Gino Parolini, 1983, quoted in Amendola (2005: 13-14)[23]

This call for a more holistic approach in the field has been the rationale behind the introduction of 'complexity' in energy analysis paving the way to a third formulation of energetics.

1.3 The introduction of complexity in energy analysis

This section briefly describes how complexity emerged in science (sect. 1.3.1) and its latent presence in energy analysis throughout the 20th century (sect. 1.3.2). Then, a critical assessment of conventional energy analysis based on complex systems theory is provided (sect. 1.3.3). This section ends with the main implications of the introduction of complexity theory in energy analysis (sect. 1.3.4).

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[23] From the lecture, *Energia: quantità e qualità*, given at the Consiglio Nazionale delle Ricerche (CNR), Roma, 11-13 April 1983. Quoted in Amendola (2005), p. 13-14 (translation by Mario Giampietro).

1.3.1 The emergence of complexity in science

Unsurprisingly, the emergence of the concept of ‘complexity’ in science has been quite complex. While some early references to complexity can be found in chaos theory, cybernetics, and other emergent fields of the late 1980s (e.g. Gleick, 1988; Morin, 1990; Kolen and Goel, 1991), there is no clear consensus on an actual formulation of an organic science of complexity. This is due to the fact that the term complexity is a semantically-rich concept very easy to convey to the general public (everything that cannot be easily represented often is called “complex”). This ambiguity results into a co-existence of various interpretations of the term in science – even in the same scientific field as in the case of biology, let alone when the meaning and role of complexity is discussed in relation to science. For instance, the theory of chaos – which notably emerged from the field of biology by studying the fractal patterns of biological systems (Mandelbrot, 1975; 1977; 1983) – corresponds to the first scientific interpretation of the complexity of nature (e.g. Bak et al., 1987) – critical organization and power law distributions – which was later turned into a branch of mathematics. Another interpretation of complexity in biology was referring to the existence of multiple scales when analyzing the organization of living systems – hierarchy theory (e.g. Allen and Starr, 1982; Ahl and Allen, 1996; Salthe, 1985).

In the specific case of the energetics of living systems, ‘complexity’ certainly can be associated with the need of using simultaneously non-equivalent descriptive domains (Neurath, 1946) reflecting the simultaneous use of multiple scales for their observation and representation. In this interpretation of complexity we can define complex systems as follows: systems that allow the observer to discern as many subsystems as needed depending on the chosen scale (or set of scales) of representation (Simon, 1962; Koestler, 1968; Pattee (ed.), 1973; Allen and Starr, 1982; Salthe, 1985; O’ Neill et al., 1986; O’Neill, 1989; Allen and Hoekstra, 1992; Ahl and Allen, 1996; Giampietro, 2003; Giampietro et al., 2011). Indeed, although the complexity of systems can be seen as a general attribute of any living system, when we move to the task of generating a quantitative representation of complex systems we have to deal with the implications of the unavoidable choice of the observer about how to interact with the observed system. In fact, if one observes the same system with a microscope, naked eye or a telescope one will obtain different typologies of observations (Giampietro, 2003). This fact entails a key epistemological problem faced by modern science: the decision of “how to observe” the external world translates into the establishment of an “observer-observation complex” that ultimately defines “what is observed” – Allen et al., 2003 (see sect. 1.3.4.1).

As we see, the interpretation of complexity in biology and ecology is more about the existence of hierarchical relations and interdependences across scales, looking for a useful description of 'functional' processes characterizing living systems. As a matter of fact, we can say that this interpretation of complexity may be used to perceive and represent 'structural complexity' or 'functional complexity' using hierarchy theory (an analysis carried out across contiguous levels of organization). This approach is at the basis of the application of 'complex systems theory' for the formulation of energetics presented here. Indeed, the integration of hierarchy theory in energy analysis has been the milestone of the second revolution in energetics although the integration of complex systems thinking was not explicit at the beginning.

1.3.2 The underlying complexity in energy analysis

The application of complex systems thinking to the relation between energy and society is not entirely new. Indeed it was underlying much of the early discussions on energy transformations in society, even though the term complexity was not explicitly used. For instance, Ostwald (1907; 1911) already suggested an alternative view on society seen as a functional body coordinating its individual organs to maximize its energetic efficiency – a characteristics typical of living systems. Later, Soddy (1926) – another epistemologist coming from chemistry – was highlighting the peculiar role of energy in economic systems. Then, the application of complex systems thinking to energy analysis was two-fold:

(1) energetic principles of living systems (FUNCTIONAL SIDE) – First, Lotka (1922) formulated a general principle to study the performance of biological systems: surviving organisms are the ones that better direct available energy into their reproduction and preservation. In the same line, Vernadsky (1926) suggested the biochemical cycles as a big picture of the energetic process of self-organization on the planet Earth. This formulation clearly individuates as a key attribute of living systems the existence of autocatalytic loops of energy flows (Odum, 1971). The strength of the autocatalytic loop is an essential factor determining the fitness of living systems;

(2) socio-economic systems as living systems (STRUCTURAL SIDE) – Second, Zipf (1941) started to compare the organizational pattern of societies to the metabolism of 'bio-social organisms'. As a matter of fact, Zipf was the first one to identify the existence of a pattern of self-organization over power laws in socio-economic systems (in fact the "power law" is also called "Zipf law" in his honor). His pioneering work individuating an expected set of characteristics for bio-social organisms can be

considered as the first attempt to define the existence of 'metabolic patterns' in human societies considered as living systems.

Additional contributions to the foundations of an 'energetics of complex systems' include the work of Cottrell (1955), the first to establish the relation between socio-economic changes and changes in the metabolic pattern associated with societal 'structure' and 'function', and H.T. Odum (1971; 1983; 1996), who applied the same set of basic principles developed in theoretical ecology to the analysis of the metabolic pattern of socio-economic systems. Yet, these attempts to formulate concepts and methods of energy analysis to be applied to socio-economic systems were not capable of reaching any kind of scientific consensus. Rather, they attracted strong criticism when they were not ignored by the rest of the scientific community. This lack of success was due to three systemic problems found in conventional energy analysis that hampered a general acceptance of the emerging field of energetics:

(i) the impossibility of defining a clear boundary for open dissipative systems both in space and time;

(ii) the epistemological challenge of how to handle and aggregate different kinds of energy flows, that makes it impossible to define the overall size of a network defined by heterogeneous energy transformations using a single quantitative mapping of energy flows;

(iii) the impredicative nature of energetic pattern (based on autocatalytic loops) in which a part of the energy output generated by a process (the energy return) must be accounted, at the same time, as the input of the process generating the output.

These three predicaments represent 'the' epistemological conundrum of energy analysis. And despite the fact that they were discussed in several dedicated workshops (IFIAS, 1974; IES, 1975; Roberts (ed.), 1978), they cannot be resolved without the introduction of complexity.

1.3.3 Critical assessment of conventional energy analysis based on hierarchy theory

For those already being familiar with the epistemological implications of complexity, it is well known that practical procedures used to generate numerical assessments within a linear input-output framework are unavoidably doomed to clash against the ambiguity and arbitrariness implied by the hierarchical nature of complex systems. Yet such a linear characterization of input-output is still the standard approach in conventional energy analysis.

The systemic methodological problems of an energy analysis based on a linear input-output analysis – which were identified as early as the 1970s (e.g. Chapman, 1974; Leach, 1975; Herendeen, 1978) – are detailed below:

(1) truncation problem – The truncation problem refers to the co-existence of multiple relevant scales of analysis due to the existence of several non-equivalent valid representations of the same process. This results in an unavoidable arbitrariness over the definition of the boundaries of analysis both in space and time when dealing with complex systems operating simultaneously at different scales. Indeed, when trying to evaluate the energetic 'cost' of a given product in a modern economy (e.g. the problem faced by those attempting an extended Life Cycle Assessment) it is impossible to include all the processes involved directly and indirectly in its production. For this reason, any analysis must be based on a sub-system of the world, a subsystem for which it becomes possible to define a plausible and finite set of inputs and outputs. This implies that the choice of a sub-system is the first crucial step in evaluating an energy cost (Chapman, 1974). However when focusing on just one sub-system of the 'whole', we do not know whether the chosen boundaries and set of inputs and outputs includes the most relevant ones nor we can know about the importance of other functional parts (and therefore additional inputs and outputs) being left out. Moreover, the scale to be adopted to study the processes generating the supply of inputs (e.g. large ecological processes) is different from the scale to be adopted to study the processes converting inputs into outputs (e.g. local technical processes of energy transformations). An input-output analysis has to adopt a scale at the time, and therefore the answer to these questions will be dramatically different depending on the chosen scale of the analysis, that in turn depends on the nature of the issue to be investigated. If we accept the epistemological predicament of complexity we have to acknowledge that systems operating simultaneously on multiple scales require the adoption of several non-equivalent descriptions (Giampietro, 2003). Therefore the choice of just one of the possible perceptions and representations of the same system – the choice of just one specific scale of analysis and related boundary definition – entails an important loss of potential information about the perceptions and representations referring to other scales. Put in another way, it is important to acknowledge that in energy analysis the choice of a scale – the narrative

used to define "what the system is" and "what it does", that in turn requires defining what should be considered as an energy input, an energy converter, useful work and the relevant processes outside human control determining favorable boundary conditions – may significantly affect both the usefulness and the pertinence of the representation.

A notorious illustration of the truncation dilemma in energy analysis is the impossibility to build a substantive quantitative assessment of the energetics of human labor. Given the amount of efforts dedicated by the community of energy analysts to this issue, this can been considered as one of the largest theoretical fiascos of energy analysis (for an overview of issues, attempts and critical appraisal of results, see Fluck, 1981; 1992; Giampietro and Pimentel, 1990; 1991; 1992; Giampietro et al., 1993).

The truncation dilemma highlights the fact that the quantification of an energy input required for a given process – as well as the energetic equivalent of a given output – depends on the information gathered at a given scale that in turn depends on the choices made in the pre-analytical step as regards to the boundary definition (Giampietro et al., 2006). When dealing with complex systems operating simultaneously across different levels of organization it is impossible to calculate a single "correct" assessment of embodied energy. To overcome the truncation problem it is essential to learn how to link non-equivalent characterizations of energy transformations across scales (see sect. 1.3.4).

(2) aggregation of different energy forms – The problem of aggregation of different forms of energy was already clear to the pioneers of energy analysis. As Long (1978) summarized it: "not all calories are equal". In fact, there are qualitative differences affecting the usefulness of a joule, which are related to the characteristics of the conversion process of one energy form to another. As a matter of fact, the classic studies of thermodynamics discussed earlier were focusing on the efficiency of thermal engines in order to deal exactly with the fact that thermal and mechanical energy are not of the same quality. The conversion of thermal into mechanical energy entails important losses! Therefore, the quantitative analysis of different energy forms requires extreme care when coming to aggregation and accounting. Joules referring to energy forms of different quality – i.e. thermal and mechanical – cannot be summed as such. To aggregate their assessments we have, first, to transform their respective quantities into a standard energy form used to define an equivalence class. This has been the rationale behind the setting of Joules of calorific value – e.g.

Tons of Oil Equivalent – as the standard to be used to aggregate different energy forms by international organizations like the International Energy Agency. However, these benchmarks can change over time – i.e. coal replaced wood in the 1970s, then oil replaced coal in the 1980s (with some exceptions such as China that is the only large country still reporting energy statistics in coal-equivalent), and now natural gas is replacing oil as a benchmark source of calorific value in international statistics. This succession in the definition of the reference "Primary Thermal Energy Source" perfectly illustrates the obvious fact that the choice of how to formalize the accounting of different energy forms ultimately depends on their use, determining the equivalence class of reference. This point is of capital importance for understanding the systemic problem of aggregation of different energy forms. As Maddox (1978, p. 136) said: "there is no unambiguous energy measure that allows one energy form to be compared to another. Energy cannot be treated as a single entity, because its various forms possess irreconcilable qualitative distinctions." Therefore, any attempt to provide a quantitative assessment in energy analysis entails pre-analytical choices over the characterization of the different relevant qualities of end uses. In turn end uses depend on the characteristics of the converters involved in the energy transformations. Again we are back to the general problem of the co-existence of multiple non-equivalent perceptions and representations of the same energy system.

To overcome this problem all together, the IFIAS recommended that *energy analysis should always display flows and assessments of different energy forms separately* (Leach, 1975). Accepting this advice requires adopting at least three non-equivalent perceptions for defining the performance of a given set of energy transformations associated with the metabolism of a society: (i) the set of gross primary energy flows – primary energy sources required by the society when interacting with its context; (ii) the net supply of various energy carriers delivered to the functional compartments of society; and (iii) the specification of the characteristics of end-uses associated with the expression of the set of expected functions required at the local scale (see sect. 1.4.3). As discussed earlier, it is impossible to describe in quantitative terms these three non-equivalent views of energy transformations using a single set of quantitative assessments. Unfortunately, in spite of this clear epistemological impossibility this is exactly the approach adopted by energy statistics to provide a quantitative representation of energy flows in modern economies . . . (Giampietro and Sorman, 2012).

(3) joint-production dilemma – The joint-production dilemma refers to the difficulty of accounting 'energetic output' and corresponding 'energetic costs' (input) when

dealing with a complex network of transformation in which more than a single output is coming from a single process of conversion (e.g. Cleveland, 2010). This problem calls back to the impossibility of simplifying complex networks of energy transformations into a linear representation (input-output) of energy flows. To make things worse, when the analysis deals with autocatalytic loops of energy (in which part of the output is fed back to the process in form of an input) we are facing a clear case of 'impredicativity' (the ultimate nightmare of reductionism), inducing non-linearity in the representation. For this reason conventional energy analysis based on a linear representation and an input-output approach entails an unavoidable failure when dealing with the perception and representation of the energetics of complex self-organizing systems. In more general terms, we can say that the joint-production dilemma is just one of the consequences of the inadequacy of simplistic representations applied to the analysis of complex energy networks. This dilemma cannot be revolved unless we first adopt a complex systems approach in energy analysis that understands and accounts for the specific characteristics of self-organizing systems governed by complex network relations.

This brief overview of the three key epistemological problems faced by energetics shows that, once we accept that the energetics of human societies is governed by a complex network of relations involving different non-equivalent forms of energy and autocatalytic loops operating across different scales, it becomes obvious that its quantitative assessment cannot be based on the traditional principles of reductionism developed by Descartes, Bacon and Newton. It is essential to develop an innovative system of accounting able to deal with the epistemological challenges listed above. The study of the energetics of living systems and human societies requires the introduction of a few theoretical concepts developed in complexity theory. In turn these concepts entail practical implications on the process of generation of quantitative information.

1.3.4 Principles introducing complexity in energy analysis

(1) It is impossible to give a substantive quantitative definition to "energy"

This principle derives from the ambiguity associated with the concept of energy in physics. As Feynman and colleagues pointed out in 1963: "we have no knowledge of what energy is . . . energy is an abstract thing in that it does not tell us the mechanism or the reasons for the various formulas". In practice, energy is perceived and described in a large number of different forms: gravitational energy, kinetic energy, heat energy, elastic energy, electrical energy, chemical energy, radiant energy, nuclear energy, mass energy, and so on. A general definition of energy, without getting into specific context and space-time scale-dependent settings, is necessarily limited to a vague semantic statement such as "the potential to induce physical transformations." Note that the classical definition of energy in conventional physics textbooks, "the potential to do work," refers to the concept of "free energy" or "exergy" which is another potential source of confusion. In fact, both of these concepts require a previous formal definition of what we define as work and a clear definition of operational settings to be applied.

Summarizing the problem associated with the ambiguity of the perception and description of "energy", Bridgman says: "the energy concept has no meaning apart from a corresponding process. One cannot speak of the equivalence of the energy of mass and radiation unless there is some process (not necessarily reversible) by which one can get from mass to radiation" (Bridgman, 1961). It shall be noted that the problem associated with the ambiguous definition of energy maps onto a more general problem over energy terms used when dealing with an energetic assessment of complex systems – 'energy' as well as 'work' and 'power' – found when trying to give a general definition that is applicable to any specific space-time scale-dependent settings (Giampietro et al., 2012).

Given this ambiguity over the concept of energy we can safely say that an ultimate quantitative definition of energy does not exist 'per se'. Rather its identity emerges only after the set of pre-analytical and empirical choices required to observe "energy transformations". So the definition of energy depends on the choices of the observer about the relevance of the perceptions about what is transformed and at which scale. This dilemma of the influence of the identity of the observer on the identity of what is observed is nicely illustrated by the famous thought experiment of the Schrödinger's cat in 1935. This thought experiment posed the counterintuitive narrative that a living system can, at the same time, have various non-equivalent identities – e.g. a cat being simultaneously dead 'and' alive before we try to look inside the box where it is locked in – a phenomenon known as 'quantum superposition' in particle physics. The main lesson from this thought experiment therefore was the controversial narrative that "information is everywhere" while, at the same time, "information 'per se' does not exist" but rather is the result of a choice made by the observer in the way it interacts with the system (in this case the decision from the observer to look inside the box the cat is locked in, hence affecting the identity of the cat). This phenomenon brings back to the epistemological dilemma of "the one and the many" posed by the very concept of complexity corresponding to the unavoidable circular relations between a complex system and its context (Morin 1990). The acknowledgment of this dilemma tamed into a coherent approach to energy analysis is what justifies the need of moving to a complex formulation of energetics.

(2) A quantitative analysis in energetics requires dealing simultaneously with multiple scales

The unavoidable existence of multiple non-equivalent perceptions and representations in energetics implies that, when dealing with hierarchically organized adaptive systems, it is virtually impossible to have "a correct assessment" of energy flows. Rather the analyst has to address a set of relevant characteristics of the processes of transformations that are level and scale dependent in order to be able to decide about the relevance of the chosen perceptions and representations. This implies that the analyst should acknowledge the co-existence of a variety of non-equivalent perceptions and representations of energy transformations across scales (from the micro, meso, and macro scale) and take responsibility for the choice of adopting only a limited set of them. Three heuristic concepts can be used in relation to the task of individuating a set of useful perceptions and pertinent representations:

(i) the concept of 'energy input' – what is the energy input needed by the system for operating properly?;

(ii) the concepts of 'power level' and 'power capacity' – what is the required level of applied power to be associated with the relevant transformations?; and

(iii) the concept of 'useful work' – what typology of tasks have to be carried out by the applied power?.

In order to provide useful information in relation to these three concepts we have to look at events taking place simultaneously at different hierarchical levels, by perceiving and representing energy transformations at different scales. This requires assigning different identities (defined at different scales) to the various elements to be described in energy analysis: the context, the whole (seen as a black-box), the parts of the whole (inside the black-box), the elements of the processes taking place within the parts.

Again this integrated description entails that the handling of different perceptions and representations over energy terms applies across scales. For example, an energy input can only be measured once we know who is using it. Therefore when dealing with energy systems we must know the characteristics of the converters – a microwave – in order to quantitatively assess the amount of energy flows going through it – kWh of electric energy. This implies that a given quantity of thermal energy (e.g. measured in MJ) associated with 1 gallon of fuel cannot be considered as an energy input for the microwave. In the same way solar radiation is not a Primary Energy Source for making electricity if one does not have available photovoltaic technology.

At the societal level, in order to be able to represent a pattern of energy flows within the socio-economic process we have to define, first of all, the integrated set of functions to be expressed. Put in another way, the analysis of the energetics of a society must start with a multi-scale definition of the identity of the set of 'end uses'. For this reason it is crucial to adopt a system of accounting that makes it possible to deal simultaneously with the various functional compartments of complex systems.

Once we accept the option of using non-equivalent descriptive domains simultaneously, we have to establish a reciprocal logical implication (self-entailment) over the definitions of identity of the various elements used in such an integrated assessment. More specifically in order to characterize the set of energy transformations required to stabilize the metabolism of a self-organizing adaptive society it is necessary to define the following pieces of information:

(i) the identity of the whole system in relation to the identity of the environment making available favorable gradients (primary energy sources and sinks for the wastes coming out from the conversions);

(ii) the identity of the converters (the organized structures in charge of energy transformations – something called 'fund elements' in the jargon of metabolic analysis);

(iii) the identity of the energy carriers (the various energy inputs of different nature used by different typologies of energy converters – something called 'flow elements' in the jargon of metabolic analysis); and

(iv) the integrated set of “end uses” (the various tasks that have to be expressed by the different compartments at different hierarchical levels in order to reproduce the whole).

When carrying out this integrated characterization, we have two couples of self-entailment among the proposed identities:

* *Self-Entailment 1*: The identities adopted for the various converters (at interface level n/n−1) referring to the power level of the converter define/are defined by the identities adopted for the energy carriers (at interface level n-1/n-2) – electricity is an energy input to an electric motor (a type of power capacity compatible with this energy form), liquid fuels are an energy input for thermal motors (a different type of power capacity compatible with this energy form).

* *Self-Entailment 2*: The identities of the set of end uses define what should be considered to be “useful energy” at the focal level n. This characterization should address the existence of autocatalytic loops making it possible the reproduction of the socio-economic process, viewed from within (at the meso-scale on the interface level n/n-1). In turn, the viability of these autocatalytic loops has to be guaranteed by a given set of tasks to be expressed at the local scale (at the micro-scale). For example, the ability of the energy sector to deliver to the society a net surplus of energy carriers (using much less energy carriers than producing) – a characteristic observable at the meso-scale – depends on the combination of net surplus generated by individual local processes of exploitation of primary energy sources (different power plants generating electricity from different primary energy sources, different extraction processes making available different types of fossil energy inputs to society).

* ***Bridging the views of the various levels into an integrated assessment***

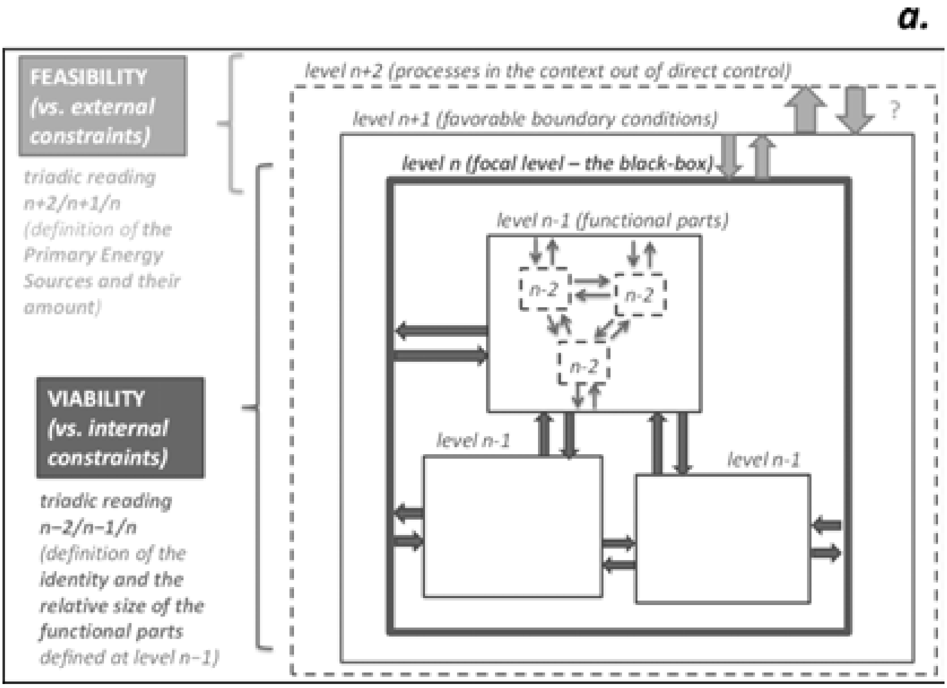
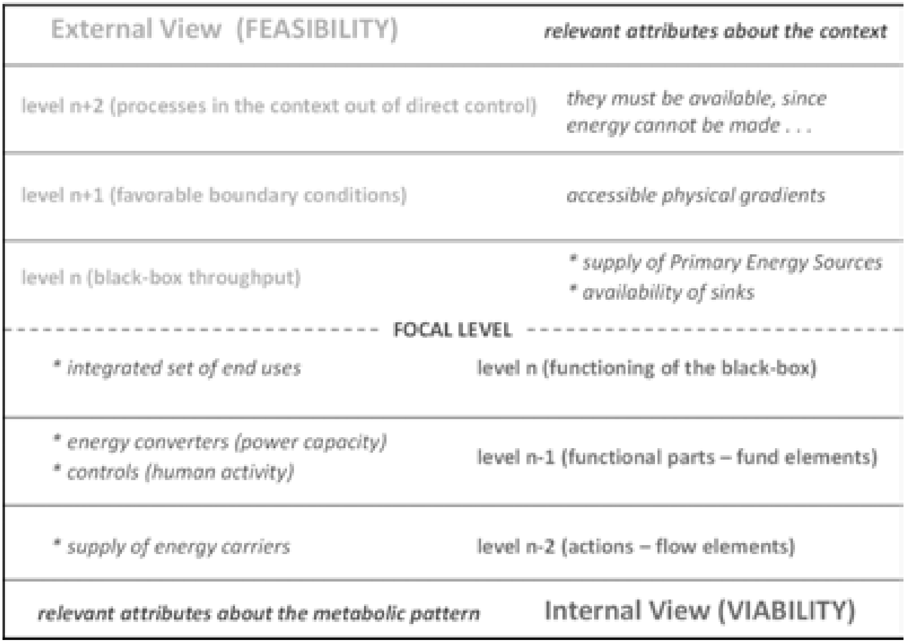


Figure 1.1 Hierarchical levels to be considered when dealing with the energetics of complex systems.

We can scale up the characteristics of local processes (e.g. conversion processes within the energy sector) to the level of whole functional compartments (e.g. the energy sector). Then we can contextualize the characteristics of the whole society in relation to the characteristics of its energy sector. In this way, we can study the compatibility of the identity defined for the whole system in relation to the identities of its internal parts (VIABILITY ANALYSIS – checking the congruence of the characteristics of flow and fund elements across the micro and meso scale). At the same time, by using a different system of accounting, it becomes possible to check the congruence of the demand of services placed by the metabolic pattern of the society on its context (FEASIBILITY ANALYSIS – checking the requirement of primary energy sources on the supply side and the requirement of sink capacity on the waste side against their availability at the macro scale) when studying the interaction of the society with its larger context.

The viability analysis is obtained when characterizing the autocatalytic loop from the inside (interface across the levels n-2/n-1/n), whereas the feasibility analysis is obtained when characterizing the autocatalytic loop from outside (at the interface n/n+1/n+2). Therefore an analysis of the sustainability of the metabolic pattern of a

b.



External View (FEASIBILITY)	*relevant attributes about the context*
level n+2 (processes in the context out of direct control)	*they must be available, since energy cannot be made . . .*
level n+1 (favorable boundary conditions)	*accessible physical gradients*
level n (black-box throughput)	** supply of Primary Energy Sources* ** availability of sinks*
FOCAL LEVEL	
** integrated set of end uses*	level n (functioning of the black-box)
** energy converters (power capacity)* ** controls (human activity)*	level n-1 (functional parts – fund elements)
** supply of energy carriers*	level n-2 (actions – flow elements)
relevant attributes about the metabolic pattern	Internal View (VIABILITY)

society requires studying the ability of a given society to express an integrated set of functions, generated by tasks carried out by the various parts that are required to reproduce and maintain the identity of the whole system. This expression is subject to two different types of constraints: (i) external constraints – the need of favorable boundary conditions determined by processes outside human control; and (ii) internal constraints – the ability of generate enough applied power (useful work) for carrying out the required set of useful tasks (functions). According to this framing of the quantitative analysis: (1) when dealing with the energetics of human societies seen as a black-box interacting with a given context (the focal level being the whole society), we are dealing with an analysis of the external constraints (feasibility), to be studied looking at the availability in the environment of the required flow of input and sink capacity for wastes; and (2) when dealing with an assessment of the performance of energy systems seen as parts operating within the black-box (the focal level being a specific energy technology such as hydropower, nuclear power, or biofuels), we are dealing with an analysis of internal constraints (viability), to be studied looking at the production factors required by the energy system to be operational. This assessment can be obtained by looking at the characteristics of standard unit operations of the system for expressing the expected tasks. For the energy sector the task to be performed is the generation of an adequate net supply of energy carriers, while at the same time keeping low the resulting waste/pollution.

** Bridging the non-equivalent representations across scales*

The non-equivalent sets of relations and identities, which depend on each other for their definitions, have to result congruent with each other when adopted in an integrated assessment. Therefore, in order to link non-equivalent characterizations of energy transformations across scales we have to acknowledge the need of organizing our quantitative analysis over nested hierarchical levels as illustrated in fig. 1.1.

In this way, non-equivalent characterizations of energy transformations, perceived and represented across scales, can be bridged by implementing two sets of forced relations:

** Bridge 1*: Conversion rates represented on different levels must be compatible with each other. This implies a constraint of compatibility between the definition of identity of the set of converters defined at level n-1 (triadic reading: n-2/n-1/n) and the definition of the set of tasks for the whole defined at level n+1 (triadic reading: n-1/n/n+1). This constraint addresses the ability of the various converters to generate "useful energy" (the right energy form applied in the specified setting) at a given rate, that must result admissible for the various tasks (specific tasks require specific power levels – e.g. the power required to lift a Jumbo jet implies that electricity is not an adequate energy input/energy carrier for that task). This bridge deals with qualitative aspects of energy conversions. It makes possible the verification of the 'viability' domain of the system defined at level n being the compatibility between the characteristics of a given set of converters defined at level n-1 in relation to the characteristics of the metabolic pattern of the whole defined at level n+1 (see sect. 1.4.3).

** Bridge 2*: The flow of energy input from the environment and the sink capacity of the environment must be enough to cope with the rate of metabolism implied by the identity of the black-box. This implies a constraint of compatibility between the aggregate size of the converters defined on the interface level n/n-1 (triadic reading: n-2/n-1/n) and the relative supply of energy carriers and sink capacity related to processes occurring at level n+1/n+2 (triadic reading: n/n+1/n+2). Energy carriers produced (inside the black-box) by the exploitation of Primary Energy Sources (interface black-box-context) will interact with internal elements of the converters (inside the black-box) to generate the flow of useful energy (interface black-box-context) and will be turned out into waste by the process of conversions (in the context). Therefore, the availability of an adequate supply of energy carriers and of an adequate sink capacity is related to the existence of processes occurring in the environment (at the level n+2) – outside human control – that are needed to maintain favorable conditions at level n+1. Put in another way, the ability to maintain favorable conditions in the face of a given level of dissipation can only be checked by considering level n+1 as the focal one (triadic reading: n/n+1/n+2). This corresponds to the verification of the 'feasibility' of the system (black-box) consisting in the compatibility between the size of the aggregate set of converters (fund elements in the jargon of metabolic analysis) defined at level n-1 and summed at the level n, in relation to the size of favorable boundary conditions defined at level n+1, which requires the existence of processes at the level n+2 guaranteeing these favorable conditions (see sect. 1.4.3).

In conclusion, when dealing with quantitative and qualitative aspects of energy transformations over an autocatalytic loop of energy forms, we have to bridge at least five hierarchical levels (from level n-2 to level n+2). Unfortunately, by definition, the environment or context (processes determining the interface level n+1/n+2) is something we do not know enough about and above all it is something about we do not have control on. Otherwise we would include these processes among those taking place inside the black-box, and we would include as parts of the modeled system. For instance, a quantitative assessment of the performance of energy systems (defined in this case at level n-1) does not account for the existence of favorable boundary conditions at the interface between the overall energy supply sector (level n – the availability of solar radiation or access to a coal mine) and the rest of society (level n+1). Let alone addressing the processes taking place at the level n+2 (the nuclear reactions within the sun generating solar radiations or the past ecological processes generating coal reserves).

Rather the system of accounting useful for assessing the performance of energy system in society has to move from micro to meso – from energy systems to the energy supply sector - and from meso to macro – from the energy supply sector to the whole society interacting with its context. This means that when dealing with the stability of "favorable boundary conditions," we can only hope that they remain the same at least for the time horizon of the analysis. On the other hand, the existence of favorable boundary conditions is a pre-requirement for dissipative systems. That is, the environment or context is and must generally be assumed to be an "admissible environment" in all technical assessments of energy transformations. Therefore, the existence of favorable boundary conditions (interface level n+1/n+2) is an assumption that is not directly related to a definition of usefulness of the individual tasks (interface level n/n+1) in relation to the issue of sustainability. This implies that the existing definition of the set of useful tasks at level n simply reflects the fact that these tasks – guaranteeing the integrated set of functions to be expressed by society – have been perceived as useful in the past by those living inside the system. That is, the existing set of expressed functions was able to sustain a network of activities compatible with boundary conditions ('ceteris paribus' at work). However, this definition of usefulness for these tasks (what is perceived as good at level n according to favorable boundary conditions at level n+1) has nothing to do with the ability or effect of these tasks in relation to the stabilization of boundary conditions in the future. In fact, the stability of existing favorable boundary conditions at level n+1 requires the stability of the processes (at times unknown and certainly outside human control) occurring at level n+2. Therefore, the information about the future stability of boundary conditions cannot be known in advance. This implies that any analysis of "efficiency" and "efficacy" can only be based on data referring to characterizations and representations that may become obsolete at any moment. The quantitative assessments are based on relevant identities determining the energetic pattern that are defined only on four hierarchical levels (out of the required five!): n-2, n-1, n, and n+1. That is these assessments are based on the 'ceteris paribus' hypothesis and reflect only information that has been validated in the past. Because of this, they are not very useful in making prediction or studying co-evolutionary trajectory of dissipative systems. More specifically, they do not study relevant processes determining the stability of favorable boundary conditions (the relevant processes taking place at level n+2). For this reason, when their analysis is based only on the characteristics of the black-box, they cannot assess "how big" is the requirement of the whole dissipative system – an extensive variable assessing the size of the box from the inside – in relation to the unknown processes that stabilize the identity of its environment at level n+2.

1.4 The 'complex formulation' of energetics

A complex formulation of energetics consists in a reinterpretation of non-equilibrium thermodynamics into practical applications able to deal simultaneously with the issue of multiple scales and multiple dimensions of analysis. This activity is known as 'multi-scale integrated assessments' (see sect. 1.4.3).

Once we accept the need for integrating conceptual principles of complexity into energy analysis, we can individuate the main features of a system of accounting able to deal with energy transformations keeping coherence and meaning across dimensions and scales. The basic rationale behind the 'complex systems thinking' approach to energy consists in a hierarchical reading of energy transformations. In particular, studying the energetics of human societies requires generating a framework describing the autopoiesis (the operation of a hypercyclic part linked to a purely dissipative part, see sect. 1.4.1) of socio-economic systems. That is, the benefit from introducing complexity theory in energy analysis is that it makes it possible to represent the forced relations across scales of the various (non-equivalent) set of energy transformations at play in living systems.

The resulting 'complex formulation' of energetics applies to both mechanical (Newtonian) systems – already described by the first 'classical formulation' – and the living systems (e.g. ecological systems, biological systems, socio-economic systems) – only described in semantic terms by the second 'non-equilibrium' formulation. That is, the first formulation of energetics is still useful for engineering applications (simple energy systems considered at the local scale) but has to be complemented by an adequate 'complex formulation' as soon as one intends to integrate the specific characteristics of complex systems described as 'self-organizing dissipative systems' (across multiple scales). As we saw earlier, this is something impossible using conventional energy analysis.

The 'complex formulation' of energetics presented in this section consists in: (1) learning how to deal with the peculiar characteristics of living systems (sect. 1.4.1); (2) providing an effective set of alternative analytical tools able to deal with their energy transformations (sect. 1.4.2); (3) generating a coherent system of accounting capable of generating a 'complex energetic accounting' known as 'multi-scale integrated assessment' (sect. 1.4.3).

1.4.1 Integration of innovative theoretical concepts

This new formulation of energetics is based on the integration of innovative theoretical concepts derived in various fields. This process of "integration by concepts" (Kapp, 1961; Spash, 2012) illustrates the interdisciplinary basis of 'complex energetics' emerging as an innovative and alternative approach able to cope with the systemic problems of conventional energy analysis. Tab. 1.1 summarizes the innovative theoretical concepts integrated in the 'complex formulation' of energetics.

Table 1.1 Integration in 'complex energetics' of theoretical concepts derived in distinct fields

Theoretical concept	**Field of origin**	**Benchmark reference(s)**
Negentropy; 'restated' second law of thermodynamics	Non-equilibrium thermodynamics	Schrödinger, 1967; Schneider and Kay, 1994
Becoming systems*	Non-equilibriumthermodynamics	Prigogine, 1961; 1978
Autopoiesis*	Complexity theory	Maturana and Varela, 1980; 1998
Holon; Nested hierarchy	Complexity theory	Koestler, 1968; Allen and Hoekstra, 1992; Ahl and Allen, 1996
Non-equivalent descriptive domains*	Complexity theory	Rosen, 1985; 2000
Semiotic process	Complexity theory	Pattee, 1982; 1995; Giampietro et al., 2006; 2011
Generative grammar	Theoretical linguistics	Chomsky, 1998
Informed autocatalytic loops	Theoretical ecology	Odum, 1971
Maximum energy flux principle; Maximum power principle; Power level*	Theoretical ecology	Lotka, 1922; Odum and Pinkerton, 1955; Schneider and Kay, 1994; Giampietro et al., 2012
Fund/flow scheme	Bio-economics	Georgescu-Roegen, 1971; Giampietro and Mayumi, 2000a; Mayumi, 2001

**: key concepts detailed in this chapter.*

Complex self-organizing systems have been studied under different labels: 'complex adaptive systems' (Holland, 2006; Gell-Mann, 1994); 'autopoietic systems' (Maturana and Varela, 1980; 1998; Kampis, 1991); ‘metabolic systems’ (Odum, 1971; 1996; Ulanowicz, 1986; Fischer-Kowalski and Haberl, 2007; Giampietro et al., 2011). Those different labels introduced several key concepts as properties making possible to describe living systems (biological systems, ecological systems and socio-economic systems) that are very useful when dealing with the energy transformations of human societies. Those four key theoretical concepts of ‘complex energetics’ derived from complex systems theory are detailed below.

(1) Autopoiesis

The concept of autopoiesis refers to the ‘circular organization’ of living systems and the dynamics of their autonomy being one of their higher-level characteristics. That is living systems demonstrate the ability to define for themselves which energy forms are relevant for analyzing their own energetics (metabolic pattern) – see definition of ‘complex systems’ in sect. 1.3.1. For this reason, it is impossible to apply to living systems the standard characterization found in classical thermodynamics (see sect. 1.2.1).

To address this issue Schneider and Kay (1994, p. 26) introduced the “restated second law” that was able to describe semantically the circular organization of the energetics of living systems: “ecosystems will develop structures and functions selected to most effectively dissipate the gradients imposed on them while allowing for the continued existence of the ecosystem”. However, Schneider and Kay also acknowledged the difficulty of formalizing the notion of entropy and entropy production in general terms for non-equilibrium systems, including living systems (systems being far away from equilibrium). This difficulty is reflected by the unavoidable ambiguity in the meaning of the expression ‘gradients’. Indeed, an operational definition of what should be considered as a ‘resource’ (favorable gradient) or what should be considered as a ‘waste’ (unfavorable gradient) for a living system is not substantive, but rather depends on the identity (i.e. the specific characteristics) of the metabolic system under study. The misunderstanding of this concept explains the persistence of the truncation problem in conventional energy analysis (sect. 1.3.3).

This particular characteristic of living systems is at the core of the very definition of ‘life’. Indeed, living systems are characterized by their ability to define their identity by forcing a given perspective on the external world (Schrödinger, 1967). This circular definition between living systems and their interaction with ‘their’ external world has been formalized by introducing the concept of ‘negative entropy’ (negentropy). That is living systems define themselves in respect to the existence of negentropy. In other words, negentropy corresponds to “the existence of a ‘system-specific’ set of favorable boundary conditions determining the possibility for the living system to discharge entropy”. The introduction of negentropy therefore made possible to integrate the autopoietic nature of living systems. In return, it entails that the definition of negentropy must be specified for every typologies of living systems.

Once we accept the unavoidable impredicativity of the definition of energetic concepts, it becomes obvious that the specific definition of potential energy of complex systems depends on the identity of the converter that is the bridge with the external world. For this reason, the general principles developed in classical thermodynamics lose their relevance as soon as we deal with living systems although they remain useful for deterministic systems: “In ecology, as in all other disciplines that treat dissipative systems, the first law is not violated, but it simply does not tell us very much that is interesting about how a system is behaving” (Ulanowicz, 1997, p. 24).

Going further on the idea of impredicativity in living systems, H.T. Odum described ecosystems as systems self-organizing by means of ‘informed autocatalytic loops’ (Odum, 1971). The existence of informed autocatalytic loops makes it possible the definition of a metabolic identity ‘frozen’ in time as describing their path-dependent definition of negentropy. That is living systems use ‘patterns of recorded information’ to guide their process of self-organization. Those patterns of recorded information act as the memory of the energetics of living systems making possible for them to deal with different energy forms in the same way that, at the micro-scale, neural circuits regulate the activity of biological neural networks (see fig. 1.4).

(2) Non-equivalent descriptive domains

Systems operating on multiple scales require the simultaneous adoption of non-equivalent descriptive domains (representations) in multi-scale analysis. The non-equivalence of representations comes from the existence of several valid perceptions over the same process depending on the chosen scale of interaction with the system. The existence of non-equivalent representations is typical of complex living systems with nested hierarchy (see sect. 1.3.1).

Considering the example of nuclear energy, it is clear that a representation with a focal level being the nuclear power plant (level n-1) – which sub-levels (n-2) are the various cooling systems, feedwater pumping systems, power-supply systems, etc. themselves made of numerous distinct equipments (n-3) – is not equivalent to a representation with a focal level being the overall 'nuclear energy system' (level n) – including the various facilities (n-1) such as the mine, the enrichment plant, the power plant or the waste-treatment plant required in the four standard functions describing the unit operations of electricity generation in power-supply systems: (1) Mining; (2) Refining/Enriching; (3) Generating power; and (4) Handling waste/Controlling pollution (Diaz-Maurin and Giampietro, 2013).

Therefore, every time we choose a particular hierarchical level of analysis for assessing an energy flow we also have to select a space-time scale at which we will describe the relative set of energy conversions (e.g. a nuclear power plant over a year or a day; a nuclear energy system over 30 years; the nuclear industry over centuries; etc.). That is, depending on the purpose of the analysis, the resulting set of relevant energy flows may be assessed over different time spans. As a matter of fact, depending on the chosen perception over the system under study, we have to adopt a non-equivalent definition of its context ('environment') and as a consequence of this choice we will generate an assessment not reducible to the others. An assessment of the energy flows of a nuclear power plant over a year will be useful for optimizing the costs of production; an assessment of the same power plant over a day will be useful for comparing the compatibility of the technology with the patterns of electricity demand. However, those two assessments will not be sufficient for dealing with the viability and desirability of nuclear energy in a context of forced energy transition. Assessing the quality of nuclear energy as an alternative energy source would require an assessment of the overall nuclear energy system considering the entire life-span of its various facilities (when considering the handling of nuclear waste defining a time horizon for assessing the identity of this complex becomes anything but easy!).

The unavoidable existence of non-equivalent representations of complex systems implies that, whatever we choose as a quantitative model to carry out an energy analysis, the various identities involved – i.e., that of energy carriers, parts, whole and environment – have to make sense in their reciprocal constraining, if we are serious about our claim of dealing with multiple scales at the same time. Obviously, this implies that distinct choices of focal level also require the adoption of distinct systems of accounting for inputs and outputs.

(3) Becoming systems

Systems far away from thermodynamic equilibrium are becoming in time because of their metabolic nature. Indeed, according to Prigogine (1978) the predicament of modeling those systems is associated with the fact that dissipative systems are always 'becoming' something else in time. This implies that a substantive formal representation of their energetic interactions with their context virtually is impossible. This problem applies to biological systems as well as to ecological and socio-economic systems that are continuously – qualitatively as well as quantitatively – evolving or coevolving with their environment. Therefore, given the unavoidable evolutionary nature of living systems, the use of a predicative representation is far from satisfactory for simulating their evolution (Giampietro et al., 2011). Moreover, the phenomenon of emergence – typical of complex living systems – implies that the representation of metabolic systems requires a continuous update of the selection of relevant attributes and pertinent approaches used for their quantitative analysis.

The existence of becoming systems points at the neglected issue of time in energy analysis. The presence of a time dimension in a quantitative assessment of energy transformations forces the analysts to deal with the issue of scale – something that is not properly addressed in conventional energy analysis (see sect. 1.3.3) – and ultimately with the notion of power corresponding to the time dimension of energy flows.

(4) Power level

The power level or metabolic rate corresponds to the ability of living systems to metabolize energy flows in time. It is essential for expressing their functions and reproducing themselves. In fact, the quest for an increased metabolic rate maps onto the very definition of life: "in the struggle for existence, the advantage must go to those organisms whose energy capturing devices are most efficient in directing available energies into channels favorable to the preservation of the species" (Lotka 1922, p. 147). This idea is also at the core of Schneider and Kay's interpretation of the second law of thermodynamics: "ecosystems develop in a way which systematically increases their ability to degrade the incoming solar energy" (Schneider and Kay 1994, p. 38).

Building on Lotka's maximum energy flux principle, H.T. Odum proposed a general maximum power principle for the development of ecological systems: "Under the appropriate conditions, maximum power output is the criterion for the survival of many kinds of systems, both living and non-living. In other words, we are taking 'survival of the fittest' to mean persistence of those forms which can command the greatest useful energy per unit time (power output)" (Odum and Pinkerton 1955, p. 332).

The introduction of the maximum power principle takes one step further the analysis of the energetics of living systems (including socio-economic systems) by bringing the time dimension back into the scientific discourse, to the extent that H.T. Odum was an outspoken advocate of the idea that this field should be based on the study of power and not on the study of energy. In fact, whereas the concepts of energy and work, as defined in physics, refer to quantitative assessment of energy without taking into account the time required for the conversion process under analysis, the concept of power is, by definition, related to the rate at which events happen. This introduces a qualitative dimension that can be related either to degree of organization of the dissipative system or to the size of the system performing the conversion of energy in relation to the processes that guarantee the stability of boundary conditions in the environment (see sect. 1.4.3).

1.4.2 Alternative analytical tools

The third formulation of thermodynamics whose general principles have been presented in sect. 1.4.1 has been turned into practice through the development of several analytical tools derived from complex systems theory. Those alternative analytical tools make it possible to perform quantitative integrated assessments of the energetics of complex systems – including human societies – that address the systemic problems of conventional energy analysis described in sect. 1.3.3. This section presents four alternative analytical tools making possible to apply the above described theoretical concepts to the study of the energetics of complex living systems.

(1) Multi-purpose grammar (from R. Rosen's modeling relation)

Any quantitative analysis dealing with complex systems operating at different scales has to be tailored on the specific characteristics of the complex system under study. That is it has to be based on the definition of the individual elements of the system – "what the systems is" – and the overall configuration of the resulting network –

"what the system does". In scientific jargon, we say that such analysis requires a pre-analytical definition of a grammar.

A grammar is a set of expected relations between a given set of 'semantic categories' and a given set of 'formal categories'. With the expression semantic category we refer to a definition of an equivalence class based on the common meaning assigned to a label. Examples of semantic categories are: "primary energy sources" (which can include fossil energy, nuclear energy, solar energy, hydropower), "exosomatic throughput" (energy input processes by a form of power capacity external to the human body), "energy carriers" (e.g. electricity, fuels, heat) or "end uses" (tasks such as illumination, transportation, refrigeration that have to be expressed within a functional compartment) that require the investment of production factors – i.e. power capacity, human control, energy input. With the expression formal category we refer to a definition of an equivalence class that can be quantified using a numerical assessment based on a defined protocol and a related measurement scheme. Examples of formal categories are Joules of thermal energy, Watt (joule per second) measuring a given form of power. In order to generate an effective quantitative energy analysis we need to handle simultaneously semantic and formal categories.

Referring to the technical jargon used in the field of software development, a grammar entails a preliminary definition of (1) a taxonomy – the set of semantic categories and formal categories used in the grammar (the types of types that are used in the grammar); (2) vocabularies for the various categories included in the taxonomy – the attributes used to individuate or characterize the elements of the different sets (relevant meanings or information; names and tokens); and (3) production rules to be applied to formal categories using the distinction between 'tokens' and 'names'.

We saw before that when dealing with complex networks of energy transformations operating across different levels of organization and scales it is impossible to generate a useful quantitative accounting using just a single protocol based on a closed set of semantic and formal categories. The need of using a grammar to make distinctions over different categories of "money" is well known in economic analysis of businesses, where numbers included in the category "gross revenue" do not have the same value as the numbers included in the category of "profit", although they are formalized using the same unit – e.g. US$. In the same way, when dealing with the energetics of modern societies different semantic categories are required for a proper accounting – e.g. "gross energy requirement" versus "requirement of energy carriers" – even when the quantitative assessment is expressed using the same variable –

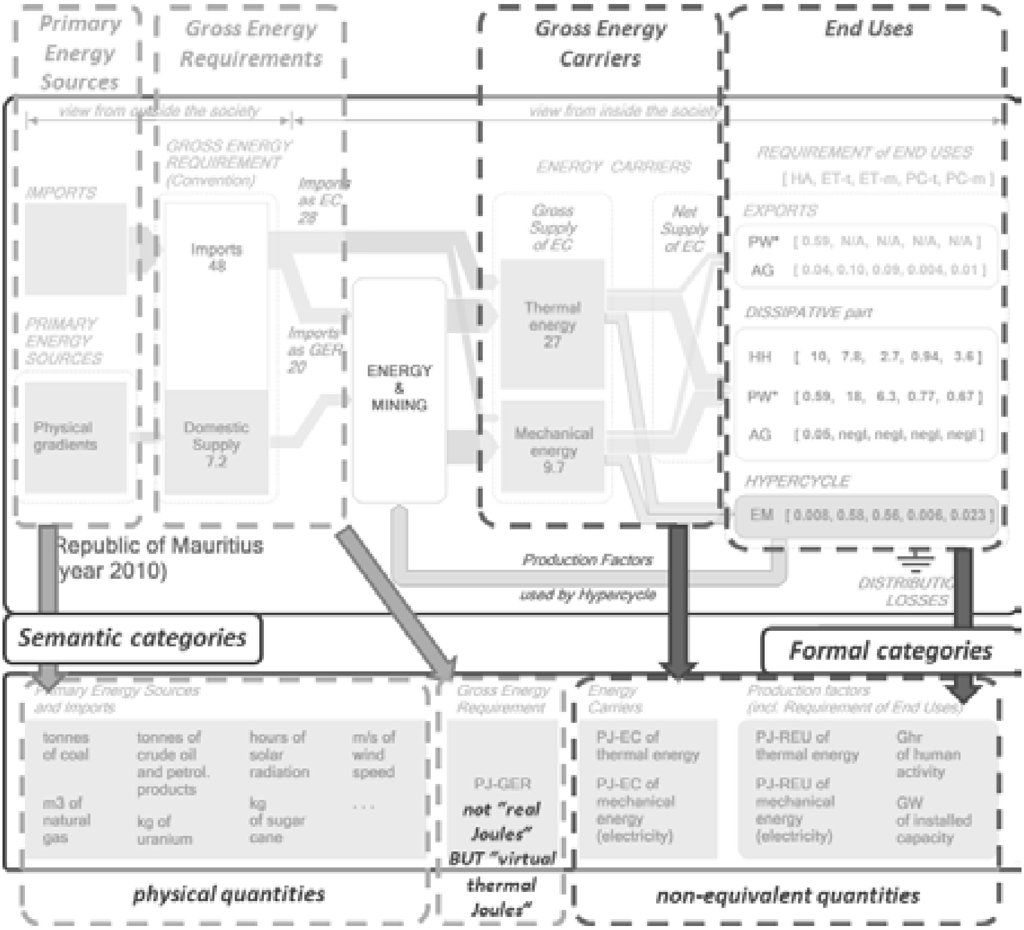


Figure 1.2 Example of multi-purpose grammar used in energy analysis (Republic of Mauritius, year 2010).

i.e. Joules. Fig. 1.2 presents a generic example of a multi-purpose grammar showing distinct semantic and formal categories useful for assessing the energetics of modern societies in relation to multiple scales of analysis.

A grammar is different from a model in the sense that it provides a description based on an expected set of relations over semantic categories and then it establishes an expected set of relations between semantic and formal categories (data and formal systems of inference). For this reason a grammar is semantically open (e.g., “cheap labor” can be formalized in different ways depending on the year and type of society; the categories describing activities in the agricultural sector can be chosen using different criteria of accuracy, let alone the fact that can be measured in different currencies!). A multi-purpose grammar defines the relevant characteristics of the system depending on other characteristics and therefore can be tailored and calibrated to specific situations and adjusted to include new relevant qualities in the analysis.

(2) Impredicative loop analysis (from theoretical ecology – R. Ulanowicz)

Society is viewed and analyzed as a nested hierarchical system using the concept of "holons" developed by Koestler (1968). Each component of this metabolic system (e.g. the energy supply sector) is part of a larger whole (e.g. the paid work sector), which in turn is part of a still larger whole (e.g. the society) embedded in an even larger process determining boundary conditions (e.g. large-scale ecological processes). At the same time, each part can be analyzed by looking at its lower-level components (the energy supply sector is composed of a set sub-systems called primary energy sources like oil, coal, natural gas, nuclear energy, hydro, etc.), which in turn can be analyzed in still smaller parts (e.g. the nuclear energy system is composed of a set of facilities like the mine, the enrichment plant, the power plant, the waste treatment plant, etc.). The definition of the identity of the various components at the different scales is based on the identification of a structural and functional relation (the holon) that can be seen (in different ways) from both the higher (as a function) and lower (as a structure) hierarchical level.

Unlike conventional (linear) deterministic models, 'complex energetics' accommodates the chicken-egg predicament typically encountered in the description of complex systems. Having established a relation between the characteristics of the whole and those of the parts of the system in semantic terms in a multi-purpose grammar, they can then be formalized in quantitative terms (using proxy variables) by generating a set of forced relations of congruence between the characteristics of the parts and those of the whole. These forced relations of congruence imply that the characteristics of the parts must be compatible with those of the whole and vice-versa, but they do not define a linear causal relation (hence the label "impredicative").

As shown above, the analysis of the energetics of complex systems requires linking the non-equivalent characterizations of energy transformations across scales. In practical terms, it means that we have to bridge at least four hierarchical levels (from level n−2 to level n+1, with an assumption about the existence of processes out of human control guaranteeing favorable conditions on level n+1) as soon as we deal with complex self-organizing systems (fig. 1.1). For this task, an autocatalytic loop of different energy forms can be used to study the forced congruence across levels of some of the characteristics of the autocatalytic loop defined on different descriptive domains (fig. 1.3).

(3) Dendrogram (from complex systems theory – P. Cilliers)

The impredicative loop analysis dealing with energy flows in relation to one fund at a time across levels (e.g. human activity across levels n/n-1) can be extended using a ‘dendrogram’ showing the forced relations between multiple flows and multiple funds across levels. A dendrogram is a pattern associated with a series of splits/divisions of a given quantity over a set of compartments (a profile of distribution) making it possible to describe the profile of allocation of the total amount of fund and flow elements over the given set of functional/structural compartments.

Referring to the technical jargon used in the field of neuroscience, a dendrogram corresponds to a ‘neural network representation’ showing the forced relations (like synapses in neural circuits) between flows and funds across levels. Such a representation makes it possible to formalize the ‘patterns of recorded information’ mentioned in sect. 1.4.1 through a set of flow/fund ratios corresponding to the benchmarks of the metabolic pattern of the systems under study. The usefulness of neural network representations (or ‘connectionist models’) when dealing with complex systems has been endorsed in the field of complex systems theory by Paul Cilliers (1998).

When dealing with the energetics of human societies we can consider three fund elements – human activity (labor), power capacity (infrastructure and technology) and land – associated with three categories of flow/fund ratios: (1) ‘exosomatic metabolic rate’ (energy flow per hour of human activity); (2) ‘exosomatic metabolic density’ (energy flow per hectare of land); (3) ‘exosomatic metabolic intensity’ (energy flow per unit of power capacity) – see fig. 1.4.

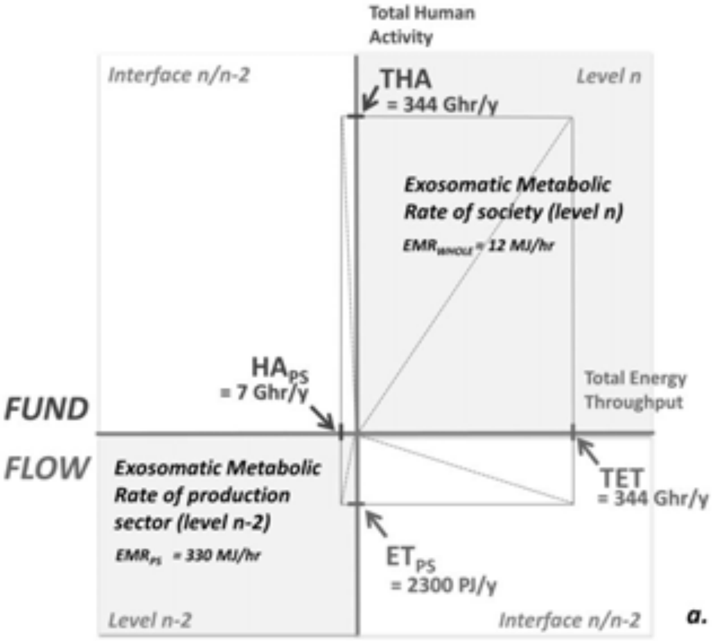
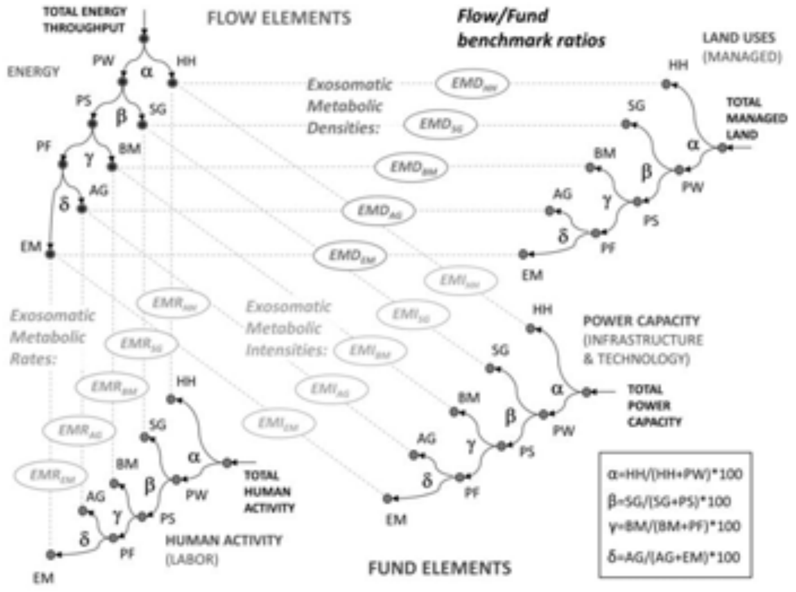
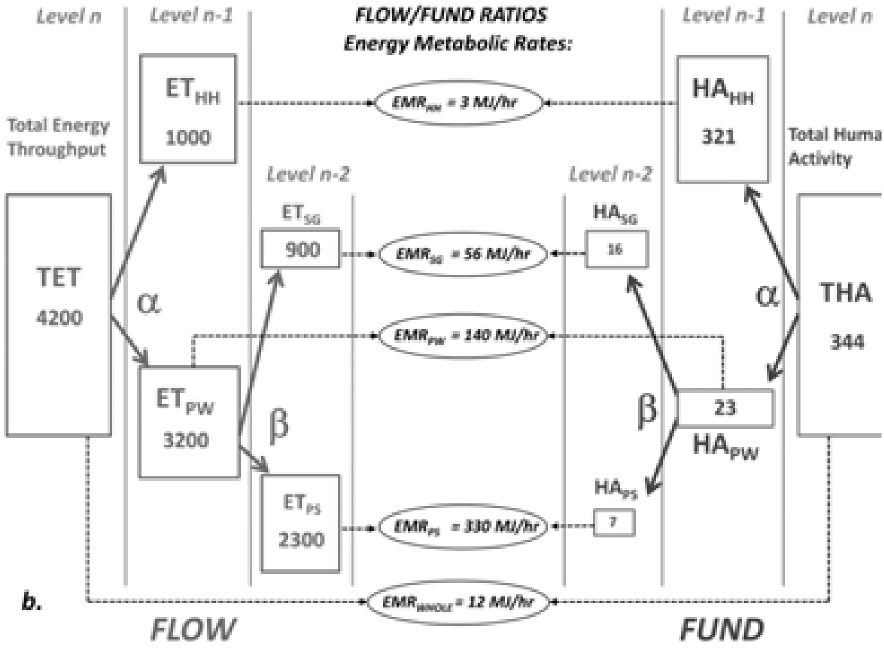


Figure 1.3 Example of impredicative loop analysis used in energy analysis (Spain, year 1999).

Figure 1.4 Example of a 'neural network representation' used for characterizing the energetic metabolic pattern of human societies.

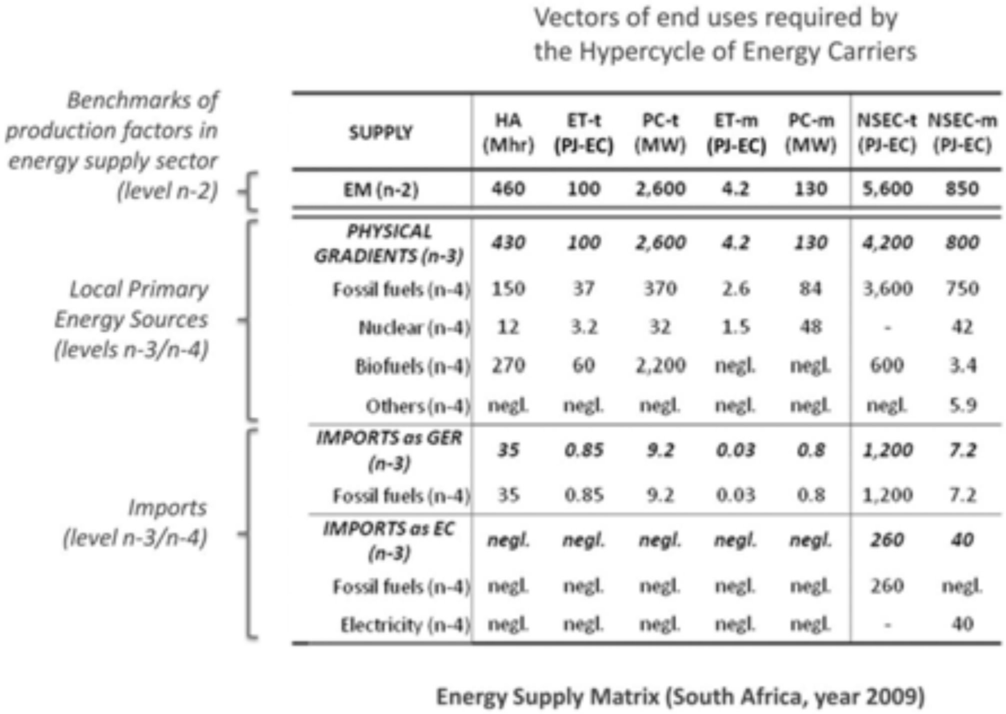




Source: after Giampietro and Mayumi, 2009.

(4) Multi-level/multi-dimensional accounting (T.F.H. Allen's Hierarchy Theory)

The application of a multi-purpose grammar to perform an impredicative loop analysis across the nested hierarchical organization of the system makes it possible to construct a multi-level/multi-dimension matrix that shows strong similarities with the popular Sudoku game (fig. 1.5). Indeed, when discussing the option space (i.e., possible scenarios of change) of a system whose metabolic pattern has been characterized in this way, we can identify the existence of a series of congruence constraints across levels (characteristics of parts/characteristics of whole) and, "at the same time", congruence constraints across dimensions (energy flows, technical requirements, labor requirements, land requirements). The definition of these constraints is similar to the rules for a Sudoku grid.



Vectors of end uses required by the Hypercycle of Energy Carriers

Benchmarks of production factors in energy supply sector (level n-2)

Local Primary Energy Sources (levels n-3/n-4)

Imports (level n-3/n-4)

SUPPLY	HA (Mhr)	ET-t (PJ-EC)	PC-t (MW)	ET-m (PJ-EC)	PC-m (MW)	NSEC-t (PJ-EC)	NSEC-m (PJ-EC)
EM (n-2)	460	100	2,600	4.2	130	5,600	850
PHYSICAL GRADIENTS (n-3)	*430*	*100*	*2,600*	*4.2*	*130*	*4,200*	*800*
Fossil fuels (n-4)	150	37	370	2.6	84	3,600	750
Nuclear (n-4)	12	3.2	32	1.5	48	-	42
Biofuels (n-4)	270	60	2,200	negl.	negl.	600	3.4
Others (n-4)	negl.	negl.	negl.	negl.	negl.	negl.	5.9
IMPORTS as GER (n-3)	*35*	*0.85*	*9.2*	*0.03*	*0.8*	*1,200*	*7.2*
Fossil fuels (n-4)	35	0.85	9.2	0.03	0.8	1,200	7.2
IMPORTS as EC (n-3)	*negl.*	*negl.*	*negl.*	*negl.*	*negl.*	*260*	*40*
Fossil fuels (n-4)	negl.	negl.	negl.	negl.	negl.	260	negl.
Electricity (n-4)	negl.	negl.	negl.	negl.	negl.	-	40

Energy Supply Matrix (South Africa, year 2009)

Figure 1.5 Example of multi-level/multi-dimension matrix used in energy analysis (investment of production factors and energy carriers in the energy supply sector in South Africa for the year 2009).

Legend: HA (human activity) expressed in Ghr (hours); ET-t (thermal energy throughput) in PJ-EC (joules of energy carriers); ET-m (mechanical energy throughput) in PJ-EC; PC-t (power capacity required for consumption of thermal energy) in MW (Watts); PC-m (power capacity required for consumption of mechanical energy) in MW; NSEC-t (net supply of energy carrier in the form of thermal energy) in PJ-EC; NSEC-m (net supply of energy carrier in the form of mechanical energy) in PJ-EC.

The example of multi-level/multi-dimension matrix shown in fig. 1.5 can be used to characterize the production factors required by the hypercycle of energy carriers of human societies (this term indicates the process, in the Energy and Mining sector, consuming energy carriers to produce energy carriers). That is the vector corresponding to the energy supply sector (EM at level n-2) can be opened into three vectors at level n-3 (referring to the three forms of energy making possible the supply: Physical gradients; Imports of primary energy sources measured as Gross Energy Requirements; Imports as energy carriers) made themselves of primary energy sources (at level n-4) either coming from local gradients or from imports. Such multi-level/multi-dimensional accounting makes it possible to tailor the focal level depending on the purpose of the analysis. For examples, it is possible (1) to discuss the relative requirements of production factors for the generation of energy carriers either if they are produced locally or coming from imports (at interface level n-3/n-4); or (2) to assess the strength of the autocatalytic loop (also called Strength of Exosomatic Hypercycle – SEH) by looking at the relative requirements of energy carriers by the whole system compared with the hypercycle at interface level n/n-1. An adequate value of SEH is an essential factor for the stability of modern societies (see sect. 1.3.2).

1.4.3 Wrapping-up the 'multi-scale integrated assessment' toolkit in 'complex energetics'

The four analytical tools presented in this section (multi-purpose grammars, impredicative loop analysis, dendrogram characterization, multi-level/multi-dimension matrix) constitute an accounting approach that is semantically open and therefore adaptable to specific situations. They provide a pre-analytical meta-structuring of the analysis (semantic framing) that is tailored to specific instances at the moment of implementing the analysis (contextualized formalization). Therefore, the final protocols of accounting may differ among different socio-ecological systems studies. However, the quantitative representation of large-scale characteristics remains sufficiently robust so as to allow cross-system comparison.

As a matter of fact, the innovative theoretical concepts together with the alternative analytical tools presented in previous sections can be turned into a 'toolkit' of integrated assessment for studying the energetics of complex systems. In practical terms, the approach known as Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM – originally proposed as MSIASM by Giampietro and Mayumi (eds.), 2000b; 2001; Giampietro, 2003; Ramos-Martin et al., 2007; Giampietro et al., 2012) has been developed as a multi-purpose grammar that explicitly requires tailored definitions of categories (when selecting semantic categories, formal categories and proxy variables) based on the specificity of different 'problem structurings' – multi-objective analysis – and different contexts, making possible a selection of indicators 'à la carte'. The MuSIASEM innovative approach to accounting can be used as (1) a diagnostic tool to characterize the existing metabolic pattern of the socio-economic system under analysis by providing integrated information on flows of energy; (2) a simulator tool to provide a feasibility, viability, and desirability check of proposed scenarios in relation to energy transitions. This approach involves the following six steps (see also Chap. 3):

(1) Definition of the socio-economic system as a set of functional compartments essential to guarantee its survival, reproduction and adaptability;

(2) Quantitative definition of the profile of investment of fund elements over the functional compartments of the system;

(3) Quantitative definition of the flows required for expressing the functions;

(4) The multi-level/multi-dimensional assessment describing the metabolic pattern across hierarchical levels and dimensions of analysis;

(5) Check of the viability and desirability domains for the metabolic pattern (definition of the internal constraints of sustainability);

(6) Check of the feasibility of the metabolic pattern in terms of resource requirement (supply side) and environmental loading (sink side) – definition of external constraints to sustainability.

Fig. 1.6 presents an overview of the toolkit used for the integrated assessment of the energetics of complex systems based on the MuSIASEM approach to accounting. This analytical toolkit makes it possible to perform two important sets of biophysical analysis in relation with the energy transformations of complex systems across levels:

* *FEASIBILITY analysis against external constraints* – External constraints are determined by the existence of favorable boundary conditions and gradients, making it possible to avoid thermodynamic constraints. In biophysical terms this refers to the possibility (either coming from availability of gradients or availability of production factors) of getting input (on the supply side) and the possibility of damping output (on the sink side). These constraints enter into play any time boundary conditions force a change in the metabolic pattern (below what could be done according to internal capacity and below what would be 'desirable'). The feasibility of a system therefore corresponds to the congruence between the energetic metabolic pattern and the bio-economic external constraints. It is assessed using two analytical tools: "Environmental impact matrix" – assessing the requirements of natural resources on

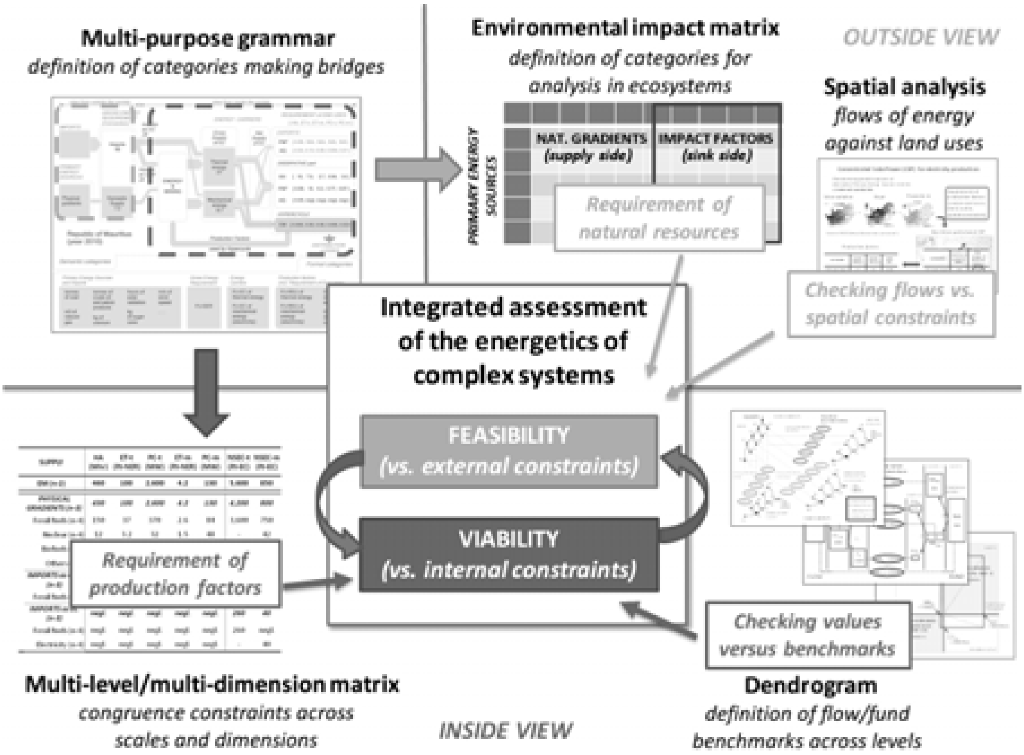


Figure 1. 6 An overview of the toolkit of integrated assessment used in 'complex energetics' based on the MuSIASEM approach to accounting.

the supply side (natural gradients) and the sink side (impact factors) – and "Spatial analysis" – checking the flows against spatial constraints based on GIS analysis.

It shall be noted that external constraints can also be interpreted looking at an additional dimension related to human preferences, cultural values, social institutions, etc. In such a case, we speak of 'desirability' against socio-economic external constraints (not shown in fig. 1.6).

** VIABILITY analysis against internal constraints* – Internal constraints are determined by the ability of the system to stabilize the metabolic pattern (in terms of power capacity, human activity, land) and economic activity (e.g. a lot of modern societies are stabilizing their metabolic pattern because of trade). These constraints are determined by the characteristics of the parts operating in the black-box determining the overall characteristics of the capability of processing flows within the black-box. Internal constraints are in play when external boundary conditions make it possible a further expansion, but the system cannot do it.

The viability of a system therefore corresponds to the ability of the system to establish a metabolic pattern of energy budget compatible with its context depending on the other compartments of the system. It is assessed using three analytical tools: “Multi-level/multi-dimension matrix” – assessing the forced relations across scales in terms of requirements of production factors; “Impredicative loop analysis” – representing the forced relations between flows and funds across scales; and “Dendrogram characterization” – checking values of flow/fund ratios against benchmarks characterizing the energetic metabolic pattern of the system under study.

1.5 Conclusion: The implications of the complexity revolution in natural sciences

Edgar Morin (1990) observed that the emergence of complexity in science appeared more as a problem than as a solution. Indeed, this was calling back to the old epistemological problem of overuse of reductionism in science. However, he also pointed out that the epistemological problem of reductionism only is the consequence of a much deeper ideological problem of ‘disjunction’ that consists in the ideological separation between science and philosophy. The negative consequences of the problem of disjunction in science only appeared in the twentieth century while in fact it dominated Western science since the Age of Enlightenment.

In fact, the use of reductionism proposed by philosophers like Bacon, Descartes, and Newton trying to simplify the complex reality to simple representations was an attempt to ‘resolve’ the problem of disjunction in re-establishing the dialogue between science and philosophy. Unfortunately, this resulted in an even worse situation with the adoption of a new ‘paradigm of simplification’ with deep ideological consequences on the way scientific knowledge is organized and interferes among the different fields. Reductionism and disjunction therefore were the two faces of the same coin of the ‘paradigm of simplification’.

The philosopher of sciences, Gaston Bachelard, however mentioned that the ‘simple’ does not exist. What exists and only in human perceptions is the ‘simplified’. This means that there is an ideological bias between the ‘simple’ – that refers the representation of the reality – and the ‘complex’ – that refers to the reality itself. The problem arises from the fact that the “blind intelligence” (Morin, 1990) resulting from the adoption of the ‘paradigm of simplification’ cannot conceptualize the unavoidable link between the observer and the observed system. The later complex relation was ironically discovered in particle physics – dealing with the tiniest – while it had been kept away from classical mechanics – dealing with the biggest of our universe. This is another illustration of the emergence of complexity in science. Nevertheless, complexity did not emerge 'per se' in science; rather this was as a result of its 'integration' in science.

Indeed, any attempt to escape from the fatal ideological attractor of 'simplification' forces the scientists to engage into a new dialectics in science ('dialogic') which translates into a strong commitment to interdisciplinary (e.g. Morin, 1990; Farrell et al. (eds.), 2013). This is what occurred with the introduction of complexity in energetics. In fact, this is the integration of available knowledge in non-equilibrium thermodynamics, theoretical ecology, and complex systems theory which demonstrated that an energetic analysis of complex networks of energy transformations is possible. It shall be noted here that complexity re-emerged in science from the very same door it had been fired out: the field of thermodynamics. In fact, the first formulation of classical thermodynamics considering "ideal cycles" (the 'simple') as the reference for representing the external world was put in trouble by the emergence of 'non-equilibrium' thermodynamics which attempted to re-introduce complexity in science by bridging the gap between biology and physics.

The lesson from the second revolution in energetics therefore is that the interdisciplinary process of "integration by concepts" proposed by Kapp (1961) makes it possible to address systemic problems found within one field. As a matter of fact, the solutions adopted for dealing with the epistemological predicaments of multiple scales in 'complex energetics' – that made it possible to reconcile claims, theories and methods in the field of energetics – could be used also to cope with the epistemological problems faced by other fields, especially in economics (Diaz-Maurin, 2013).

Indeed, like Joseph A. Schumpeter used to say before the rise of neoclassical economics, the whole field of economics is once again in "state of crisis" (Schumpeter, [1931] 1982). This is due to the fact that the current paradigm of neoclassical economics demonstrates persistent and increasing failure at solving old and new problems that is how crises are recognized in science (Kuhn, 1962). As a matter of fact, it is clear that similar integration efforts are urgently needed in economics in order to tame the evident contradiction between neoclassical economics and much of the knowledge developed in natural sciences, especially in thermodynamics and ecology (Georgescu-Roegen, 1966; 1971).

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Chapter 2
The nuclear energy system

> *In producing power from fission, we are creating radioactivity on an unprecedented scale—a scale that humankind has had absolutely no experience with. Whether this technology that produces such vast amount of radioactivity will be accepted by the public is an open question.*
>
> —Enrico Fermi, in spring 1944, quoted in Weinberg (1992: xii)

This chapter provides a critical assessment of the conventional perception and representation of nuclear power. In particular, it takes the case of how risks from nuclear power have been conventionally assessed, revealing some systemic misconceptions about the very notion of risk and explaining the systemic controversy of this technology. The chapter ends by proposing such an alternative representation of the "nuclear energy system" based on lessons from complex systems theory developed in Chap. 1. Adopting such an alternative view is crucial for assessing the viability and desirability of nuclear power as an alternative energy source.

2.1 The nuclear predicament

2.1.1 The unresolved problems of nuclear power

The recent accidents of Fukushima in Japan put back to the attention of the public opinion the historic debate over nuclear energy. This debate between those in favor and those against the civil use of nuclear energy has been traditionally based on three unresolved problems (i) proliferation/terrorism; (ii) consequences in case of accident; (iii) long term management of radioactive waste. Yet, there is another fourth unresolved problem, which is systematically neglected in the discussion over the desirability of nuclear energy: (iv) the systemic lack of economic competitiveness of this technology as a producer of electricity. This low economic competitiveness seems to be extremely clear to possible private investors – which are abandoning nuclear – but it is never considered as a crucial issue in scientific discussions about the viability and desirability of nuclear energy as an alternative energy source.

The systemic problem of the low economic competitiveness of nuclear energy

The civil use of nuclear energy for the production of electricity already went through difficult times from the mid-1970s to the 1990s, when the world turned its back to this industry, with some exceptions such as in France where the nuclear industry was established and, since then, ruled by the State. Contrary to popular belief, the end of the first era of nuclear energy did not happen as a consequence of the accidents at Three Mile Island (United States, 1979) and Chernobyl (Ukraine, 1986) but earlier. Indeed, as shown in fig. 2.1, a wave of cancellations of new nuclear reactors already started in 1974 in the U.S. – before the Three Mile Island accident – and the period of cessation of new orders lasted until the early 2000s. This seems to indicate clearly that none of the three unresolved problems mentioned earlier had anything to do with these cancellations. In fact, in the early 70s no relevant events changed the perception of US investors about them (see Chap. 6). As result of this cessation of new orders, almost all nuclear reactors that are now in operation in the US were ordered between 1965 and 1973 (Bodansky, 2004). This fact suggests that the real source of trouble for the industry seems to be a systemic lack of economic competitiveness rather than anything else (Bradford, 2012; 2013).

Looking at the history of the nuclear power industry, we can identify a first period of nuclear blossoming – called “great bandwagon market” – in which nuclear power was expected to soon become the silver bullet capable of solving any energy crisis once and for all (see Chap. 6). At that time many were expecting that nuclear power would become cheaper than coal-fired power to the extent that Lewis L. Strauss – former Chairman of the US Atomic Energy Commission and one of the pioneers of the industry – was envisioning a future in which electricity, thanks to nuclear power, would have become “too cheap to meter” (Bodansky, 2004). This “belief”, however, turned out to be wrong (Yang, 2009; Smil, 2010). Although orders of nuclear reactors were sustained until a year after the oil embargo in 1973 when the investors were still thinking that the economy would rely more on electricity after the oil crisis (Yang, 2009), the expected cost decline never happened (Bupp and Derian, 1978; Grubler, 2010). Since then nuclear energy for the production of electricity was never enough competitive to re-gain interest from investors. Even worse, some analysts indicate that the learning curve of this industry over this first period was negative in terms of economic costs (e.g. Grubler, 2010). The more it was learned about how to make safe reactors, the higher their cost.

Then, in the recent years, despite the urgent need for alternative energy sources capable of reducing the dependence of modern societies on fossil energy, nuclear energy still faced troubles to convince investors of developed countries. For instance, in the US the number of applications for new reactor licenses submitted to the US Nuclear Regulatory Commission (US NRC) has actually decreased over the last few years despite the federal 2005 Energy Policy Act (US Congress, 2005) proposing tax incentives and loan guarantees for building new reactors (Bradford, 2010). Moreover, the design certifications of reactors of third generation are being delayed (Bidwai, 2011). In Europe, delays and over-costs encountered for the French EPRs that are still under-construction in Finland and in France also undermine the chances of a second era for nuclear energy (Bidwai, 2011). As Bradford (2012) puts it, "the most

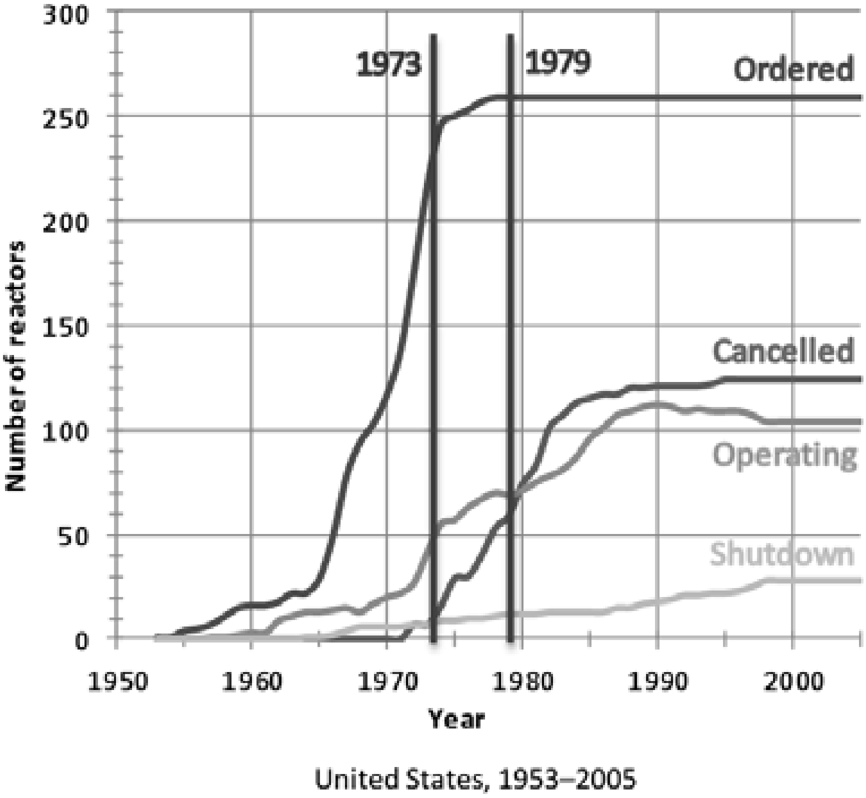

Figure 2.1 Evolution of the number of nuclear reactor in the United States, 1953–2005.

Source: US EIA, 2006.

implacable enemy of nuclear power in the past 30 years has been the risk not to public health, but to investors' wallets". For this reason, some suggest that economics has always been and will remain the deciding force in the nuclear energy landscape.

Given the situation in Europe and in the US where the nuclear energy market is locked, it seems very difficult that a worldwide "nuclear renaissance" could actually happen any time soon even if some developing countries prospecting to acquire new nuclear reactors due to their growing economies (Bradford, 2010). Moreover, today, after the Fukushima nuclear accidents in Japan chances are that the worldwide nuclear slowdown will continue, as indicated by the German decision to rapidly phase out nuclear energy from its portfolio of primary energy sources (Fairley, 2011). Even in the US, the decision from the NRC Atomic Safety and Licensing Board (ASLB) to deny the Calvert Cliffs-3 construction/operating license for that reactor – considered as the flagship of the "nuclear renaissance" as being the first new reactor project to submit an application in about 30 years – illustrates the current difficulties found by nuclear power to convince local governments and investors (NIRS, 2012). In fact, in this very symbolic case, the reason for denying the application has been only in seemingly caused by a legal issue – the applicant (namely UniStar) being owned 100% by a foreign company (namely the French company, Electricité de France) something that is prohibited by the Atomic Energy Act. In reality, the core reason is that UniStar has been unable to build a partnership with a US utility in order to get the application approved due to the lack of genuine interest in new nuclear reactors in the U.S. (NIRS, 2012).

Wrapping up the history of the industry, many observers (e.g. Coderch Collell, 2009; Smil, 2010; Bradford 2012) conclude that nuclear energy for the production of electricity has demonstrated a low economic competitiveness since the very beginning of its deployment and that it is very likely that this problem will remain the same also in the future (Bradford, 2013). To make things even worse, we can expect that additional (costly) safety features will be required by the licensing agencies for the design of new reactors as a logical response to the Fukushima nuclear accidents.

The inability to resolve these problems has made nuclear power controversial and there is no reason for this to change given the misconceptions present in current attempts to address them.

2.1.2 The unreachable consensus about nuclear power

Since the very first stages of the use of nuclear energy to generate electricity, the question of the costs and benefits from this technology has always been a major obstacle to find any consensus. Indeed, even in the early 1970s – before any major nuclear reactor accident ever happened worldwide – experts were already considering that "the public perception and acceptance of nuclear energy [...] has emerged as the most critical question concerning the future of nuclear energy" (Weinberg, 1976: 19). Today, one has to admit that the acceptance of nuclear power is still a very active issue that has even been amplified after the Fukushima accidents (e.g. Slovic, 2012).

In fact, when discussing about nuclear power in comparison with other alternative energy sources, one easily finds contrasting (and even opposite) perceptions over its viability and desirability. In the case of nuclear safety for instance, proponents claim that nuclear energy is "safe" or "secure" – or at least that it is "becoming safer" – and that accidents are "normal" (Perrow, 1984; 2011; Pidgeon, 2011), part of any learning process of a given technology, and that nuclear power actually is responsible for very few fatalities compared to other technologies (e.g. Sir David King in: Harvey 2011; Monbiot, 2011). On the other hand, opponents to nuclear power claim that accidents demonstrate that nuclear power is "unsafe" or "dangerous" and that accident-induced radiation represents a major threat to both humans and the environment (e.g. Greenpeace Africa, 2011). In addition, nuclear power can also appear as "clean" and "cheap" to some, whereas "dirty" and "not cost-effective" to others. To the extent that nuclear power can *simultaneously* appear as "clean, secure and cheap" to some, whereas "dirty, dangerous and not cost-effective" to others (fig. 2.2), which illustrates the chronic controversy of nuclear power.

In scientific jargon, the problem associated with the unavoidable existence of non-equivalent legitimate perceptions on the normative side is called *social incommensurability* (Munda, 2004, 2008). In such situations, scientists are facing a clear dilemma when trying to use science for governance of controversial technologies. In the case of nuclear power, they are dealing with a clear predicament: How to decide whether it is "good" or "bad" to have a lot of nuclear power plants? Who are the social actors whose values should be considered? What are the most useful perceptions associated with this issue? How to consider the preferences of future generations that in the next century will have to deal with the wastes?

Figure 2.2 Contrasting perceptions about nuclear power.

Fig. 2.2a: Nuclear power seen as a "clean", "secure" and "cheap" source of energy by employees of the nuclear industry in the U.S. (Source: CFECE, 2008).

To better understand the "nuclear predicament" encountered by any scientist when discussing the desirability of nuclear power, it is useful to look deeper at the problem of nuclear safety that is one of the main factors of the chronic controversy of this technology. For this purpose, it is useful to look at how risks from nuclear power have been conventionally assessed, hence revealing some systemic misconceptions about what risk is and how it can be discussed in scientific terms.

2.2 Debunking the controversy about nuclear safety

The controversy of nuclear power can mostly be attributed to the impossibility to generate a shared perception about the risks involved with the use of this technology. Here I provide a critical review of the way risk is considered in quantitative terms based on available scientific knowledge over risk. Then I present two wise scientific takes about risk that are missing in those conventional methods, and how they can be used to reconsider the notion of risk from technology and nuclear power in par-

b.

South Africa, March 2011

Fig. 2.2b: Nuclear power seen as a "dirty", "dangerous" and "not cost-effective" source of energy by protesters in South Africa. (Source: Greenpeace Africa, 2011).

ticular. By doing so, it becomes possible to check the relevance and usefulness of the representation of nuclear power in the discussion about its desirability.

2.2.1 The historical debate about the quantitative assessment of risk

"The atomic industry could take a catastrophe like Chernobyl every year."
—Hans Blix (1986, in his capacity as director of the IAEA)

Since the very beginning of the use of quantitative analysis to assess risk of technology in the 1970s, there has been a strong and still unresolved debate among experts over the validity of using such methods when dealing with situations of uncertainty.

The debate originated among risk assessment experts over the way to deal with risks from technology in quantitative terms. First, Farmer (1969) argued that safety analysis should be conducted within the framework of "design under risk". In this view, the use of reliability analysis is aimed at evaluating the probabilities of failure as well as the various consequences. Weisman (1972) opposed this idea by saying that safety analysis cannot be limited to internal failures but has to also deal with remote, external events and consequences that do not affect the plant reliability but might affect public health and safety. Then the problem is that in relation to these additional potential failures information is not and will not be available.

Weisman (1972) therefore proposed to conduct safety analysis within the framework of "design under uncertainty" which is defined as "situations in which failure rates are allowed to vary outside the range of believed possible". In this view, "the most desirable system is that which minimizes the total expected cost". In doing so, he proposed a quantitative risk assessment method associated with safety design that consists in an objective function:

> *Minimize* $p_i\left[E(C_i) + E\left(C_p\right) + E(C_s)\right]$,
>
> *where* $E(C_i)$ *is the expected costs incurred when a given failure occurs* $E\left(C_p\right)$ *is the expected cost of the additional protective equipment required to achieve the failure level* p_i, *and* $E(C_s)$ *is the expected cost of the additional safety equipment needed to obtain the failure cost* $E(C_i)$.
>
> —Eq. (18) in Weisman, 1972.

This function assumes that both (1) the value of the system failure probability p_i can be estimated by computer programs; and (2) the expected costs of failure $E(C_i)$ can be known in advance. However given that there exist doubts about the availability and validity of the information used to estimate those values – a situation typical of irreducible uncertainty, see sect. 2.2.2 – such function cannot but adopt an approach that consists in considering "as reasonable as possible" risks (Farmer, 1969). This actually refers to the typical problem of monetary valuation (which elements to include and how to 'price' them) and of discounting found in cost-benefit analysis (e.g. Munda, 1996).

Given the fact that long term consequences are not bounded (e.g. Slovic, 2012), Weisman (1972) introduced the notion of "social costs" which consist in having governments setting the "maximum expected failure cost" through the definition of liability limits whereas every cost beyond this value inherently is turned into social costs that therefore are part of the safety design. This logic points at the notion of "acceptability of risks" whose epistemological implications were not evident to their proponents at the time. In fact, to them, this procedure is considered as being "highly conservative" for the good reason that "since the likelihood of such an accident is very low, the actual risk to the population would be far below what the population itself indicates it is willing to accept" (Weisman, 1972: 404). This conceptualization over the perception and acceptance of risks were shown too simplistic by later developments in psychology science (see sect. 2.2.2).

The "Weisman vs. Farmer" debate corresponds to the historical bifurcation in safety analysis as far as how to deal with risk in quantitative terms – a sort of "supply vs. demand" dualism about risk pointing at the idea that end users must be defined before risk can be formalized (see Chap. 1). We will see that none of these two approaches led to this consideration in practice. This debate let to the development of two main approaches to quantitative assessment of risk associated with the use of technology: the *deterministic* approach and the *probabilistic* approach. These two approaches imply considering that the processes associated with technology can be reduced to either a deterministic or a stochastic system.

The deterministic method focuses on the evaluation and control of the consequences of accidents while the probabilistic method focuses on the estimation of the probability of occurrence of accidents. This approach thus consists in ensuring that the consequences are under control. On the other hand, the probabilistic approach first consists in demonstrating that the probability can be kept to *acceptable* values. These two approaches therefore seem to be fundamentally different as far as their interpretations of the notion of risk:

* *deterministic approach* – The system is said to be deterministic when all its possible outcomes and probabilities are assumed to be known in advance and their consequences are controlled. Conversely, the deterministic characteristic of a system is a pre-requisite for being able to assign probabilities! As a matter of fact, the quality of the analysis depends on the ability of the expert to anticipate the largest set of possible and undesirable situations. In that sense, the deterministic approach refers to – and is limited by – situations of "risk" as defined in sect. 2.2.2. That is, the deterministic approach to risk loses completely its validity as soon as the system is shown to face uncertainty.

* *probabilistic approach* – The probabilistic approach mainly differs from the deterministic approach in the sense that it requires setting first "the upper limit of hazard which may then be accepted or rejected" (Farmer, 1977). This means that all the

possible outcomes (under the scope of the assessment) must be known by the analyst. Then, the quality of the analysis only resides in improving the representation so as to predict what will happen with higher accuracy. That is, the effort of the analyst using the probabilistic approach resides in reducing as much as possible the indeterminacy about the known outcomes so as to increase the accuracy of the quantitative evaluation of their probabilities – this is the sole criteria setting its validity. Following this probabilistic approach makes it possible to consider the system as being stochastic. That is all its possible outcomes are assumed to be known and only their relative probabilities are subject to doubt. However in doing so the resulting analysis is only able to deal with indeterminacy, which is the *quantifiable* form of uncertainty, see sect. 2.2.2. That is, the probabilistic approach to risk loses completely its validity as soon as the system is shown to face *irreducible* uncertainty (ignorance), see sect. 2.2.3.

These two quantitative methods to assess risk from nuclear power have been used in different ways depending on the countries. For instance, in France the generally preferred approach to risk has been so far the “deterministic” method while in the United States the “probabilistic” approach has been preferred since the late 1970s (e.g. Rasmussen et al., 1975). The fact that different methods are used to assess risk in different countries refers back to a cultural explanation to risk perception (e.g. Renn, 2008). Indeed as shown above, adopting a probabilistic approach to risk for instance is like trying to manage risk in terms of *acceptability* (see sect. 2.2.2). In return, the definition of what is acceptable or not acceptable for the people is a political act as it results from a deliberative choice which is implicitly cultural. This refers back again to the problem of social incommensurability that is in fact the source of all troubles of quantitative risk analyses.

Indeed, the two conventional quantitative methods to risk do not differ as regard to their conceptualization of risk in the sense that they both refer to situations where information about the set of possible outcomes can be known and their probabilities of realization can be estimated. As such, they only differ in relation to what actually is considered as known outcomes under the scope of the analysis: the deterministic approach attempts to integrate all possible failure modes, whereas the probabilistic approach solves this by stating the boundaries beyond which risk is not considered under the design (rejection criteria). This fact points at a systemic problem in the pre-analytical choices made over the meaning of “safety”. Indeed, according to these two methods the “safe/unsafe” (or “dangerous/non-dangerous”) duality defining the first boundary of “risk” is reduced to the “possible/impossible” duality (deterministic method). But, since information space is unavoidably limited, which translates into doubt on the actual set of possible outcomes, risk experts have been forced to adopt the “acceptable/unacceptable” duality (probabilistic approach). Yet, in doing such pre-analytical choices over the definition of risk, they inherently generate an incompatibility between the output of quantitative risk assessment methods and the conceptualization of risk among the public – let alone the discrepancy between the output of quantitative approach and the reality of the consequences observed in practice (see box 2.1). This is due to a dilemma faced by risk experts who are asked to *reduce* risk from a complex technology to one single number – when not simply asked to reduce it to essentially “zero” (e.g. Slovic, 1984; Suzuki, 2011) – facilitating decision-making and communication which turns out to be an ineffective strategy in the long run that generates frustration given that “risk” is by nature a semantically rich concept whose definition differs among social groups (see sect. 2.2.2).

Coming back to the problem of quantifying risk, deliberating over the acceptability of consequences for the individual or the environment from a potentially hazardous activity is possible only to the extent that it remains within the realm of known possible outcomes. No deliberation over acceptability of hazards can be made on unknown possible outcomes, unless the deliberation process acknowledges the presence of irreducible uncertainties and genuine ignorance (see sect. 2.2.2). This explains why there has been strong criticism from those working on risk governance about the effectiveness and usefulness of the rationale of the probabilistic approach to risk for the governance of technology and of nuclear power in particular (Funtowicz and Ravetz, 1990; Wachinger et al., 2010; Slovic, 2012).

Yet the use of those methods in spite of these epistemological problems has implications. Indeed, the systemic controversy about nuclear power is factored by the fact that the public generally is not involved in the pre-analytical step consisting in the choices over the set of attributes used to define risk, compared to the widely use of “expert judgments” (e.g. Keeney and von Winterfeldt, 1991; Meyer and Booker, 1991; Otway and Winterfeldt, 1992; Pyy and Pulkkinen, 1998; Clemen and Winkler, 1999; O'Hagan et al, 2006) – yet, the unavoidable existence of biases in people’s perception of probability in situations of risk is long-time known from psychologists (Festinger, 1957; Simon, 1976; 1987; Ross, 1977; Tversky and Kahneman, 1974;

Kahneman and Tversky, 1979; a review in Wachinger et al., 2010) something that go against a strategy based on the elicitation of expert judgments. In the end, we reach a chicken-and-egg dilemma where the lack of participation of the public in the pre-analytical choices over risk increases the distrust in the industry, hence the legitimate perception of risk that should be considered by the industry. This tension over the definition of risk from nuclear power have led to the existence of a “perception gap” between experts and lay people on the meaning of risk (Slovic, 2012; see sect. 2.2.2) implying that it will never be possible to reach any consensus about the future of nuclear power, in spite of the fact that this discussion is very relevant in the context of a global energy crisis.

Box 2.1 The controversial introduction of the probabilistic approach in nuclear safety design and governance.

The introduction of the probabilistic approach to risk assessment in nuclear safety design is due to Norman C. Rasmussen, a former professor of nuclear engineering at the Massachusetts Institute of Technology. In 1975, he headed the publication of a report (Rasmussen et al., 1975) for the Nuclear Regulatory Commission (often called the “Rasmussen Report”). This report received a worldwide attention as it introduced the formal discipline of probabilistic risk assessment (PRA) in the field of nuclear safety design whose methods are now used routinely in the nuclear industry but were limited to the aeronautics and spatial industries at the time. According to the Rasmussen Report, the risk of a nuclear power plant failure was low, with a core damage accident occurring only once in every 20,000 years of operation in the U.S. – one reactor running for one year counting as a year of operating experience. However, in 1979 – only four years after the Rasmussen Report was published – a partial meltdown occurred at the Three Mile Island 2 reactor in Pennsylvania, when the nuclear industry in this country had fewer than 500 years of operating experience. A new study ordered by the Nuclear Regulatory Commission therefore reassessed the risk and estimated it at one meltdown per 1,000 years of reactor operation, 20 times more frequent than in the Rasmussen Report. This was the first “lesson learned” allowing to improve the PRA-based design of nuclear power plants.

Nowadays, the current core damage frequency (CDF) of the current generation-II reactors is claimed to be between about 5×10^{-5} per reactor-year or one core damage every 20,000 reactor-years (as originally evaluated by the Rasmussen report in 1975 for the U.S.) in Europe (Leurs and Wit, 2003) to one every 50,000 reactor-years (or 2×10^{-5}) in the U.S (Gaertner et al., 2008) – so far, the PRA analyses performed on nuclear power plants have shown that core melt frequencies range from 10^{-6} to 10^{-3} per reactor-year (Wu and Apostolakis, 1992). With about 440 nuclear reactors currently operating worldwide, this should correspond to one core damage every 45 to more than 100 years. Yet, with three new core damage accidents at Fukushima-Daiichi nuclear reactors 1, 2 and 3[24] – in addition to the two core damage accidents at Three Mile Island in 1979 and Chernobyl in 1986 – this gives us with 5 core damage accidents in less than 40 years. That is, one core damage accident happens every 8 years on average in the World since 1970 (or one core damage accident happening about every 2,000 reactor-years) – this is 10 times more often than according to the design claims! – corresponding to the beginning of operation of generation-II reactors (very few generation-I reactors remain operating today). This discrepancy between the nuclear safety assessed by quantitative methods and the number of accidents observed in practice illustrates the limits of relying on quantitative methods to risk assessment used for governance of nuclear power.

The introduction of the probabilistic logic into risk assessment and governance has been strongly debated since the beginning of its development and still is very active today. Criticisms are mainly articulated around the problem of expert's judgment (e.g. Elster, 1979; Hänni and Smith, 1986; Mosleh, 1986; Mosleh et al, 1988; Wu and Apostolakis, 1992; Parry, 1996) and about the inadequacy of using this approach when dealing with governance of technology (e.g. Volta and Otway, 1986; Renn, 2008; Wachinger et al., 2010).

It should be mentioned here that the consideration of "uncertainty" in quantitative risk assessment methods refers in fact to the same concept of risk by considering "uncertainty" as a reducible quantity assumed to be known (stochastic probabilities about a set of possible outcomes) – for an illustration of this confusion, see e.g. Kirchsteiger (1999). Therefore conventional quantitative methods, even when referring to the term "uncertainty", do experience the same epistemological problems as the methods based on risk.

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[24] The three partial core-meltdown have been confirmed by TEPCO and announced by the French ASN authorities on 15 March, 2011 (Press release no. 9). URL: http://www.asn.fr/

Yet there have been attempts to account for *complexity* in quantitative risk assessment methods (e.g. Helton, 1994; Leveson, 2004; 2012). However, in those methods, the conceptualization of complexity referring simply to the existence of hierarchy in systems, without a proper consideration of the issue of scale in the analysis (see Chap. 1). This does not solve the epistemological problems when attempting to quantify uncertainty. Moreover these attempts still adopt a reductionist approach to complexity and ignore the problems of *emergence*, a key characteristic of self-modifying complex systems, very well-known in other scientific fields such as theoretical ecology. Therefore, those methods have nothing to do with a proper integration of complex systems theory in quantitative analysis, something badly needed in sustainability science (Chap. 1). As a matter of fact, the consideration of "uncertainty and complexity" found in available literature does not solve the systemic problems found in quantitative risk assessment methods and actually suffer themselves from the same problems identified in this section.

This brings us to the widely acknowledged shortcomings when trying to forecast state changes of complex systems such as the collapse of ecosystems or the outbreak of epidemics (Nature Editorial, 2013). This impossibility of reliable predictions is due to the fact that so far "no 'one-size-fits-all' property has been found that signals the imminent collapse of a complex system" (Boettiger and Hastings, 2013), and we will never be able to find such a property in the future (Perrow, 1984; 2011). Acknowledging the implications of the complexity of nuclear systems should be one further reason to abandon the use of quantitative methods in situations of irreducible uncertainty.

The problems raised in the previous section are well known from those working on risk assessment and governance. The general tendency to focus more on the aspects that we know in order to avoid to have to deal with irreducible uncertainty and ignorance is to avoid situations in which it is impossible to use quantitative analysis. This strategy applies to both popular discourses – where mainstream media tend to focus only on narratives and issues where science is less affected by uncertainty (and ignorance). This tendency implies a systemic bias against controversial issues, such as for instance the science of climate change (e.g. D. Fisher, 3 January 2012), sticking on scientific discussions where it is suggested that "we should focus on dangers that we can control, and particularly on those of our own creation" (Nature Editorial, 8 January 2013). Unfortunately, adopting such a strategy is like burying one's head in the sand rather than trying to deal with the realities of risk.

2.2.2 The forgotten scientific knowledge about "risk"

> *Science is the belief in the ignorance of experts.*
>
> —Richard Feynman (1999: 187)

> *If "complete ignorance" is rare or nonexistent,*
> *"considerable" ignorance is surely not.*
>
> —Daniel Ellsberg (1961: 660)

Early scientific discussions over risk have been intimately related to the development of the mathematics of chance and probabilities (Cardano, 1663; Pascal and Fermat, 1654; Laplace 1829). In fact, before the emergence of such quantitative methods, the natural way of dealing with risk was to rely on the laws of Gods and fates (Bernstein, 1996). This explains why discussions over risk have almost exclusively been associated with mathematical formalization and quantitative methods since then, to the extent that *risk* and *probabilities* often are considered as being two sides of the same coin. Yet, later developments in distinct scientific fields during the twentieth century made it possible to improve the conceptualization of risk in two ways. First, on the formal side, the work of F. Knight (1921) in economics makes it possible to distinguish situations of *risk* from situations of *uncertainty* and *ignorance*. Second, on the normative side, psychometric studies developed by the Oregon Group (e.g. Fischhoff et al, 1978; Slovic et al, 1980; Slovic et al, 1986; Slovic, 1992) indicate that risk is *perceived*, so that is cannot be defined in absolute terms nor reduced to a probability in specific situations. As a matter of fact, by bringing these two advances together it becomes possible to conceptualize the notion of risk in a broader and richer way, something badly needed when using science for the governance of technology, and of nuclear power in particular.

(1) Risk refers to perceptions

In parallel to the debate over the quantitative approaches to assess risk, a debate among psychologists emerged as far as how to formalize risks and benefits in governance of technology. Indeed the very same year Farmer proposed his “design under risk” approach to safety, Starr (1969) adopted the logic of economic equilibrium by proposing a “revealed preference” approach to risk-benefit analysis relying on economic risk and benefit data. In doing so, he was assuming that society was able to reach an optimum between the risks and benefits associated with the use of a technology in the same line that society was able to set an upper limit to the acceptance and rejection of risk in the probabilistic approach to risk. This approach was later strongly criticized on the basis that the emergence of an alternative narrative stating that risks and benefits rather result from “expressed preferences” when using psychometric analysis based on questionnaire data (e.g. Fischhoff et al., 1981). This view was later turned into what has been called the “psychometric paradigm” ([16-24], in Slovic, 1987).

Psychometric studies have shown that “risk” associated with the use of technologies is a notion subject to divergent interpretations depending on the social groups (e.g. Slovic, 1987; 1999; Renn, 2008). On the one hand, risk analysts usually consider under the label of “consequences of risks” the immediate hazards induced by a technology (pre-analytical choice in semantic terms) and reduce it to one scalar (e.g. “expected number of fatalities per year”, Burgherr and Hirschberg, 2008) – the formalization – in their associated quantitative assessment models – the representation. On the other hand, lay people demonstrate a basic conceptualization of risk that is semantically much richer as depending on different perception factors (Fischhoff et al, 1978; Slovic, 1987; Renn, 2008), hence difficult to formalize under the reductionist approach of quantitative assessment methods. For instance, a technology will be considered as more or less risky depending on the trust in the managers of the technology or the appreciation of its direct benefits (see sect. 2.2.3). These contrasting perceptions of risk show that several non-equivalent interpretations of risk can coexist implying that discussions over risks induced from the use of technology cannot be reduced to one single number generated by a quantitative model. As a matter of fact, there cannot be any scientific proof when dealing with risk since it cannot be defined in substantive terms. In fact, as Slovic (1999) summarizes it very well: “whereas danger is real, risk is socially constructed”. Risk therefore is a social representation of the reality of hazards. And as for any representation that results from a perception, there exist unavoidable non-equivalent legitimate representations of risk. This problem called *social incommensurability* represents *the* epistemological problem of any attempt to deal with risk in quantitative terms as it cannot be defined in substantive terms. For this reason the psychometric paradigm was opposing the "usefulness of questionnaire techniques" to Starr's "laws of acceptable risks" (Fischhoff et al, 1978), which was later generalized in the need to switch from "truth" to "quality" in governance of risk (e.g. Funtowicz and Ravetz, 1990; 1992; Wachinger et al., 2010).

Findings from risk perception research therefore forced risk analysts to abandon the search for "absolute risks" and, at the same time, be very careful with the logic of "acceptable risks". In doing so, they could use the scientific insights about the logic of the public's attitude toward risk.

Moreover, the perception and acceptance of risk depend on social and cultural factors (e.g. Fischhoff et al, 1978; Slovic et al, 1980; Slovic, 1987; Lemkow, 2000; 2002; Pidgeon et al. (eds.), 2003; Renn, 2008; Wachinger et al., 2010). Among those factors, psychometric research (Slovic et al, 1985; Slovic, 1987) has shown that perception and acceptance of risk are driven by two main factors: *information about* the risk and *control over the risk* – labeled as "unknown risk" and "dread risk" respectively in those studies. They also indicate that each one of those factors results from a combination of characteristics that reflect the semantically rich conceptualization of risk among individuals (Slovic et al, 1985; Slovic, 1987; Renn, 2008):

(1) Information about the risk – Risk is *perceived* as being higher in situations where risk is either "not observable; unknown to those exposed; effects are delayed; risk is new; risks are unknown to science". Those characteristics all refer to the availability and reliability of information as regard to the risk being perceived.

(2) Control over the risk – Risk appears to be less *accepted* in situations where risk is considered as being either "uncontrollable; dread; catastrophic potential; fatal consequences; inequitable distribution of risk and benefits; affect future generations; cannot be easily reduced; increasing; involuntary". Those characteristics all refer to the possibility of control for the risk being accepted.

These two factors of risk are very relevant for comparing the public's attitude toward different technologies and eventually illustrates why some are controversial (fig. 2.3).

In particular, these two factors make it possible to study the systemic controversy of nuclear power compared with other energy sources. Here it should be reminded that, once we accept the fact that risk results from a psychological process of perception and acceptance, it is clear that risk cannot be defined in absolute terms. This refers to the problem of what we could call *individual incommensurability* about risk (not to be confused with the social incommensurability coming from the non-equivalent perceptions among different individuals). That is risk from any activity or technology cannot but being defined *relatively* to another even among one single individual. This is why, questions used in psychometric studies on the perception of risk are of the following logic: “Do you think that A is more risky than B?” or “On a scale from 1 to 10, to what extent would you rate the risks from A, B, and C?”. This further explains why it would be a non-sense to qualify nuclear has being *risky* or *not risky* in substantive terms, just like it is impossible to qualify it as desirable or viable “by default” due to the unavoidable presence of social and technical incommensurabilities. The unavoidable existence of the *individual incommensurability* (defined at the psychological level) affecting the definition of risk implies that even discussions around risk based on perception by different social groups must be relative. That is, the individual incommensurability which resides among one individual remains even when different individuals can express similar *relative* perception of risk or are part of a “social group” expressing a shared perception – see sect. 2.2.3 which studies the perceptions of risk from nuclear power relatively to other energy systems, and other controversial technologies. For this reason risk perception from a given technology can change over time as well as it cannot be compared with a perception made in another analysis at another time. The implications of the individual incommensurability further explain why a better conceptualization of risk cannot be integrated in quantitative risk assessment methods, without making a detrimental simplification. This refers back to Arrow’s impossibility theorem that is at the basis of social multi-criteria analysis.

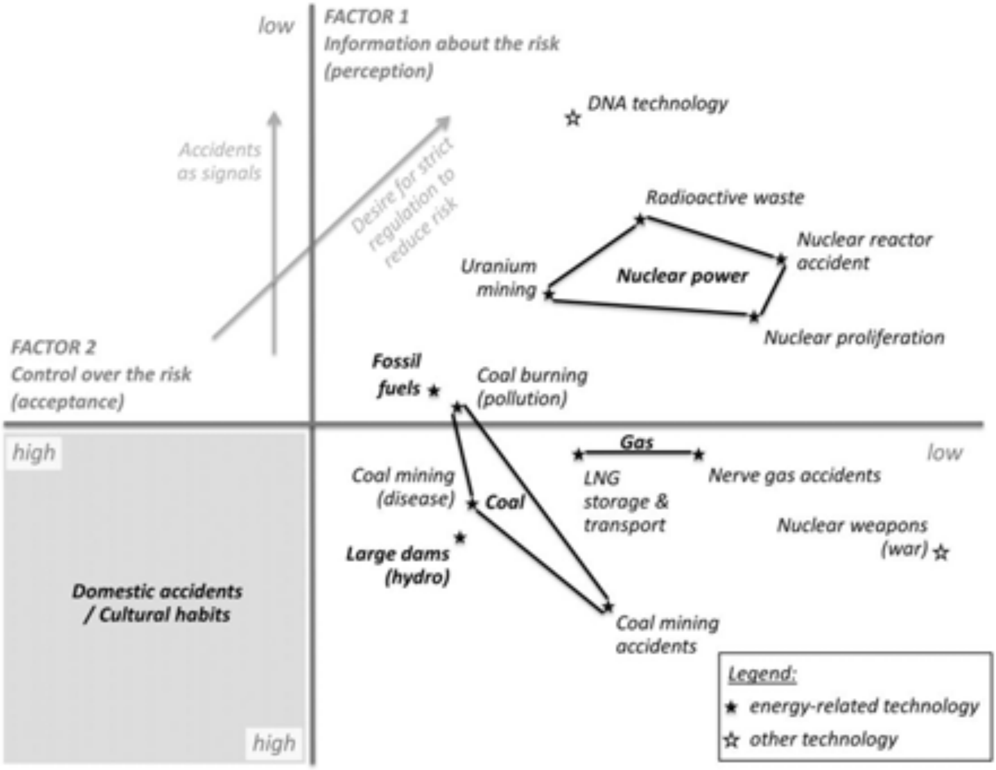


Figure 2.3 Factors of risk perception and acceptance various energy sources and other controversial technologies.

Source: after Slovic, 1987.

(2) The distinction between risk, uncertainty and ignorance

In his famous book "Risk, Uncertainty and Profit", F. Knight (1921) made the distinction between cases in which it is possible to use previous experience in order to predict what will happen from cases in which inference is impossible. Following this distinction, quantifying risk requires being able to apply a distribution of probabilities to a given set of possible outcomes that are known in advance, while uncertainty refers to situations where probabilities are unknown although the outcomes are known. Although his study in economics was of "pure theory", it represents the first scientific attempt to distinguish *risk* from *uncertainty*.

Later, Rosen (1985) recalled the difference that exists between a natural system and its "representation" through models. Evaluating risk therefore requires having valid models able to forecast what will happen in space and time. Yet, since any "representation of natural systems" requires dealing with a finite information space, one faces (1) an inevitable loss of some qualities of the natural systems at stake, and (2) an unavoidable "expiration date" of the validity of the modeling relations. The notion of risk in relation to systems therefore is constrained by these two factors. That is in situations where it is not possible to predict with accuracy what will happen in space and time one can no longer speak about risk *per se*. In that case, one actually is confronted with *uncertainty*, or with *indeterminacy* in that particular case. Indeterminacy corresponds to situations in which there is information but at the same time there is doubt about the validity of this information. That is, indeterminacy resides in the impossibility to predict with accuracy what will happen although information exists. This is the typical situation of nested hierarchical systems (e.g. weather forecast, nuclear reactor) for which information about each variable does exist but it is impossible in practice to predict all possible outcomes (e.g. the failure modes of a nuclear reactor) due to the high sensitivity to initial conditions requiring to deal with a virtually infinite amount of information.

Finally, Kampis (1991) introduced the notion of 'self-modifying systems' (e.g. human societies, ecosystems, as well as the "nuclear energy system" described in sect. 2.3) for which there is an unavoidable and continuous emergence of new relational functions (new interactions and new contexts). In presence of self-modifying systems one faces another form of uncertainty that is called *ignorance*. Ignorance corresponds to situations where there is awareness of an impossibility to predict because the space of relevant information is inaccessible. That is in situations of ignorance, relevant information simply does not exist so that it is not that predicting is not accurate enough (indeterminacy) but that predicting purely is impossible (e.g. Hoffmann-Riem and Wynne, 2002; Ramos-Martin, 2003).

Bringing together this knowledge, one can distinguish three typologies of situations as regard to risk (see also Giampietro, 2002):

* *situations of risk* – Situations in which the set of possible outcomes can be predicted in space and time using models or probabilities. In situations of risk, the probabilities of occurrence of an outcome and its consequences can be assessed.

* *situations of uncertainty (indeterminacy)* – Situations in which it is not possible to know in advance the set of all possible outcomes, and it is not possible to assess it

with accuracy the probabilities of the known potential outcomes due to too much information and/or high sensitivity to initial conditions.

** situations of ignorance (irreducible uncertainty)* – Situations in which it is clear that the set of relevant outcomes is simply unknown hence neither probabilities nor consequences can be known.

Therefore, by assessing the availability and validity of information, one can know when it is risk, indeterminacy or ignorance. It is only once this distinction has been made that one can check the validity and usefulness of the different typologies of representations of "risk" about the operation of a given technology. For example, in the particular case of nuclear power we can study the relevance of using conventional risk assessment models in light of the above scientific distinction between risk, uncertainty and ignorance. In fact, to each typology of risk can be associated with a typology of representation: (1) a deterministic representation, where the system is assumed as having a mechanical behavior, is valid in situations of risk only; (2) a stochastic representation, where the system is assumed as having a random and chaotic behavior, is valid in situations of risk and indeterminacy; and (3) a complex representation, where the system is assumed as being governed by self-organization and emergence, is valid in situations of risk, uncertainty and ignorance. Validity domains of the typologies of representations against risk are summarized in fig. 2.4.

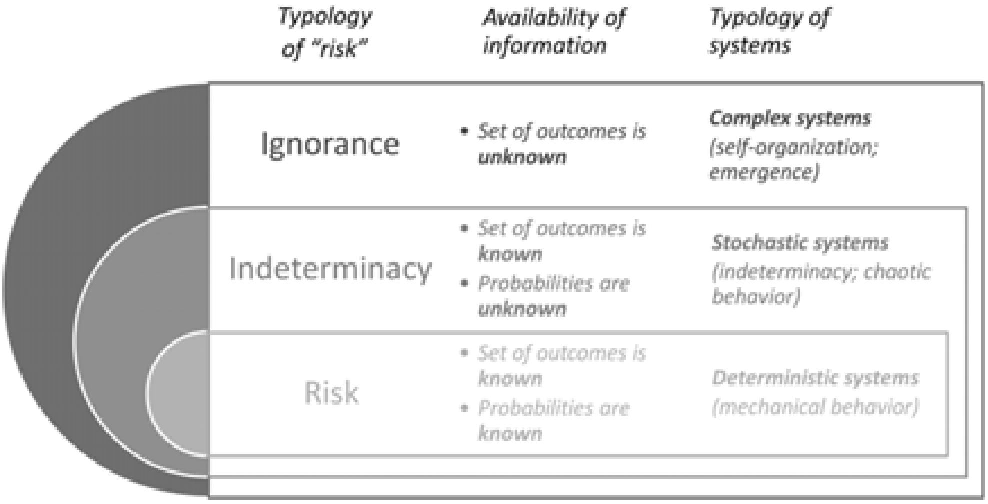


Figure 2.4 Validity domains of typologies of representations according to typologies of risk.

By looking at which typology of risk a given representation is referring to, it becomes possible to check the validity of the representation in relation to the nature of the system under study. Rosen's distinction between a natural system and its representation through models tells us that since models reflect only a limited information space, they are inherently affected by uncertainty (indeterminacy) and depending on the circumstances by ignorance. For this reason, it is not wise to only rely on models for discussing risk unless systems are proved as being purely deterministic or stochastic. As a matter of fact, any sound discussion over the risk involved with the use of a technology requires identifying when we are in situations of risk, uncertainty or ignorance. This is particularly relevant in the case of nuclear power as dealing with the three types of situations (see sect. 2.2.4)

Given the presence of sources of uncertainty and ignorance affecting the "nuclear energy system", the use of quantitative methods must be limited to situations of pure risk where information exist and consequences can be controlled, that is in situations where no other system interacts with the nuclear reactor and its internal components, as well as outside situations of interactive complexity (Perrow, 1984; Leveson, 2012).

The implications of the distinction between risk, uncertainty and ignorance are complex. Indeed, when increasing the information space – an uncertainty-to-risk transfer which generally consists in focusing on performing further research on *known* uncertainties so as to create greater certainty (Hoffmann-Riem and Wynne, 2002) – one unintentionally generates new sources of uncertainty and in some cases ignorance (e.g. Faber and Proops, 1998; Ramos-Martin, 2003). That is, the effect of new knowledge is unknown! One illustration of this problem has been the probabilistic seismic-hazard estimates which has been more severe over time (Bommer and Abrahamson, 2006). To make things even worse, in the specific case of seismic hazards, available knowledge in seismology is not properly integrated in nuclear safety design whereas the unavoidable ignorance about geoscience is essentially ignored by the engineers in their quest for quantifying risk (Nöggerath et al, 2011). As a matter of facts, when dealing with risk, the more we know on the one hand, the less we know on the other hand. In its "Global Risks Report" the World Economic Forum clearly states this problem:

> *With new information, the perceptions and realities of risks change, and often in unforeseen directions. Consider that in some circles the threat from greenhouse gas emissions made nuclear energy seem less hazardous than fossil fuels over the long run. Yet the nuclear catastrophe in Fukushima, Japan, not only changed public perceptions there but also energy policy, almost overnight, in some parts of Europe.*
>
> (WEF, 2013: 14)

As a matter of fact, in such situations it is crucial to learn how to deal with changing perceptions of risk about a technology.

2.2.3 Reconsidering the 'risks' from nuclear power

(1) The different factors of risk from nuclear power

As seen in sect. 2.2.2, risk perception and acceptance respectively result from the availability of information about the risk and the possibility of control over it. More specifically the acceptance of risk from a given technology – hence attitudes toward it – is primarily conditioned by perceptions of direct benefits and by trust in the managers of this technology (Slovic et al, 1991; Slovic 1999; Siegrist et al, 2000; Whitfield et al, 2009; Slovic, 2012). As result of this fact, attitudes toward nuclear power are a function of perceived risk, and both attitudes and risk perceptions are a function of values, beliefs, and trust in the institutions in charge of its governance (Whitfield et al, 2009). The problem resides in the fact that contrasting perceptions over risks and benefits from technology are based on non-equivalent values. This is why greater benefits do not compensate perceived risks – rather trust does (e.g. Whitfield et al, 2009) – which falsify the use of cost-benefit economic models in the governance of risk from technology.

On the other hand, trust tends to enhance perceived benefits and reduce perceived risks (Siegrist et al, 2000; Whitfield et al, 2009), and as such represents the ultimate factor of risk from a technology. Yet trust itself is conditioned by values which must be shared between the people and the managers of this technology. If this sharing is established, then this establishes social trust (Siegrist et al, 2000) generating positive attitudes toward it (Whitfield et al, 2009). Unfortunately, this is not the case with nuclear power for which the public systematically perceive this technology as riskier than risk-assessment experts (Slovic et al, 1979a; Hardeman et al, 2004; MacGregor et al, 2002b; cited in Slovic, 2012). The apparent impossibility of reaching any consensus over the perception of risk from nuclear power suggests that the public and the industry simply do not share the same values. Moreover, the systemic distrust from the public in the nuclear industry is doubled by the fact that direct benefits of this technology remain unclear to them. Indeed, people perceive it as “uncertain”, hence making their perceived risks higher and less accepted than those of other energy sources (see fig. 2.3). To worsen the situation in relation to trust, there is a disagreement about what can be considered as knowledge claims over this technology. That is the frontier between what is claimed as known and ignored in relation to nuclear power still is not clear and actually is a room for debate (see box 2.2).

In addition, trust is a fragile phenomenon as it requires a long period of time to be achieved while it can be destroyed quasi instantaneously (Slovic, 1999). For instance, before the accidents at Fukushima the confidence in nuclear safety from the public was increasing since the 1990s in the US up to a never attained situation where perceived benefits slightly exceeded the perceived risks (Jenkins-Smith, 2011 in Slovic, 2012). Yet, the fear over nuclear power regained public at large almost overnight after the Fukushima accidents. In fact, many observers found problems of communication during the nuclear crisis (e.g. Funabashi and Kitazawa, 2012; Nature, 2012) which may explain the increasing distrust between risk experts and the public with worsening effects on the perception of risks involved with nuclear power (see sect. 2.2.3). Yet, some (e.g. Pidgeon and Fischhoff, 2011) claim that one way to improve public confidence in relation to the risks from technology resides in better communicating to non-specialists risks and uncertainties involved each time a technology has a significant technical content (e.g., nuclear power, genetically modified crops, nanotechnology, climate change). I would argue that it may be the other way around.

In fact, communication about risks from technologies involving significant technical content often is too simplistic and eventually worsens the situation of distrust. One of the best illustrations of such miscommunications about nuclear power is the use of the "banana equivalent dose" which consists in comparing the radiation dose absorbed by a person in case of a nuclear reactor accident to the number of bananas (which contain naturally occurring radioactive potassium) that the same person would have eaten to reach this additional dose. However, although comparisons are generally more meaningful than absolute numbers or probabilities to people, such "apple-to-oranges" comparisons, on the contrary, may confuse and anger people (Slovic, 2012).

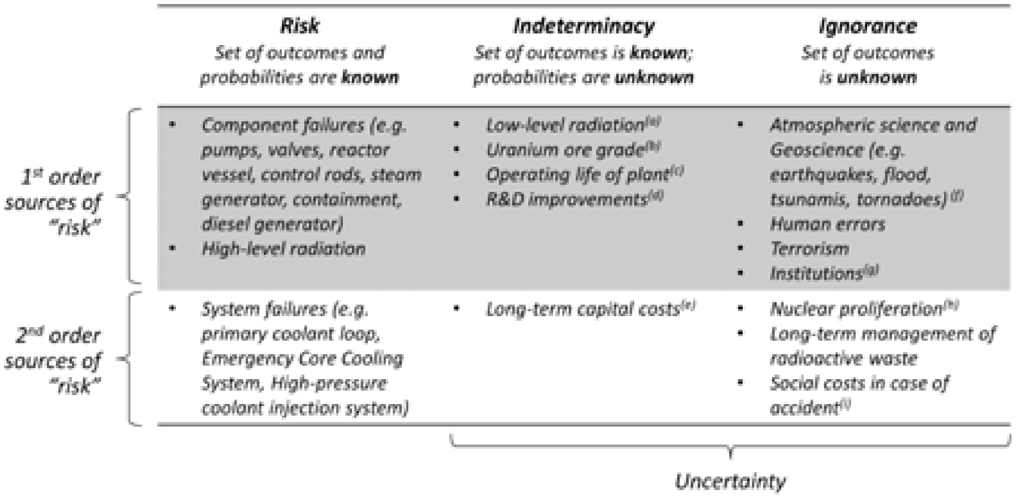
In fact, communicating about risk certainly is useful. But the usefulness and relevance of such communication over the risks and uncertainties involved with a given technology depends on the difference between the perspective from scientists and the perspective of non-specialists who already have their own perception, in spite of having less information about the technology. For this reason, when proposing "risk communication" scientists should be very careful to avoid making normative communication. In fact, distrust may become a chronic situation due to the unavoidability of accidents coming from the use of nuclear power as from the use of any other complex technology (Perrow, 1984; 2011; Pidgeon, 2011). One way to cope with the problem of distrust between risk experts and the public may in fact consist in being more transparent about the limits of the knowledge available for the governance of risks from a given technology. Indeed as Hoffmann-Riem and Wynne (2002) summarize it: it may be more important to emphasize on uncovering the limits of knowledge (uncertainty and ignorance), rather than on proving existing knowledge to be correct (risk). In doing so, they insist in the "need to recognize and address the crucial distinction between uncertainty and ignorance" so that non-specialists can make their own opinion about the acceptability of those "risks" based on the available scientific knowledge generated by the scientists. In practical terms this means that governance of risks requires first and foremost to distinguish and deliberate over the three typologies of situations discussed earlier: (1) when risk is controlled; (2) when there is some doubt about the information used to generate risk assessment (uncertainty as indeterminacy); and (3) when it is impossible to know what can happen (ignorance).

(2) The different sources of "risk" from nuclear power

The shared general formalization of risk from nuclear power among risk assessment experts is that they consider risk as the product of probability and magnitude, where the magnitude corresponds to the consequences of an outcome and is generally reduced to its immediate impacts to health (e.g. number of people killed or injured) and to infrastructures (e.g. amount of property damaged). When adopting such definition of risk, for example, coal mining is represented as being more risky than nuclear power due to its higher death toll (e.g. Monbiot, 2011). Yet, letting alone the epistemological flaws of such over simplistic conceptualization of risk and the problem of dealing with probability discussed in sect. 2.2.2, Slovic (1987) indicated that actually "the accident at the Three Mile Island (TMI) nuclear reactor in 1979 provides a dramatic demonstration that factors besides injury, death, and property damage impose serious costs". That is, non-equivalent perceptions can also be found on what should be included under the label "magnitude" in case of an accident. In fact, as Fischhoff and co-workers (1984: 125) observed: "The controversial aspects of that choice can be seen by comparing the practices of different scientists. For some, the unit of choice is the annual death toll (e.g., Zentner, 1979); for others, death per person exposed or per hour of exposure (e.g., Starr, 1969; Wilson, 1979); for others, it is the loss of life expectancy (e.g., Cohen and Lee, 1979; Reissland and Harries, 1979); for still others, lost working days (e.g., Inhaber, 1979)." That is, subjectivity not only affects the choice over the probabilities but also the choice over the units used to evaluate the magnitude which can vary depending on the perspective of the scientist both in space and time. This implies that there is no objective reasons for limiting the discussion over the risks involved with the use of nuclear power to the immediate dangers which refers back to the problem associated with the consideration of social costs (see sect. 2.2.1). The problem, however, resides in evaluating the long-term consequences of a nuclear reactor accident that imply typical situations of indeterminacy (e.g. health effects of low-level radiation) and ignorance (unknown failure modes).

In fig. 2.5, we identify the main sources of "risk" relevant for deliberating over the desirability of nuclear power. These sources of risk from nuclear power can be classified two cross-categories:

(1) typology of risk – risk, uncertainty and ignorance, as discussed in sect. 2.2.2. In fact, after having distinguished situations of risk, uncertainty and ignorance it be-



	Risk Set of outcomes and probabilities are **known**	**Indeterminacy** Set of outcomes is **known**; probabilities are **unknown**	**Ignorance** Set of outcomes is **unknown**
1st order sources of "risk"	• Component failures (e.g. pumps, valves, reactor vessel, control rods, steam generator, containment, diesel generator) • High-level radiation	• Low-level radiation(a) • Uranium ore grade(b) • Operating life of plant(c) • R&D improvements(d)	• Atmospheric science and Geoscience (e.g. earthquakes, flood, tsunamis, tornadoes) (f) • Human errors • Terrorism • Institutions(g)
2nd order sources of "risk"	• System failures (e.g. primary coolant loop, Emergency Core Cooling System, High-pressure coolant injection system)	• Long-term capital costs(e)	• Nuclear proliferation(h) • Long-term management of radioactive waste • Social costs in case of accident(i)

Uncertainty

Figure 2.5 Sources of risks, uncertainty and ignorance of nuclear power.

Legend: (a) US EPA, 2012. However, the problem of knowledge in relation to the effects of low-level radiation on health is discussed in box 2.2. (b) Lenzen, 2008; van Leeuwen (1985; 2006). (c) Defined in van Leeuwen (1985) as the product of technical life and the average load factor, and measured in 'full-load years'. (d) Anadon et al, 2012. (e) Including (i) uranium mining and milling at low ore grades, (ii) construction of the nuclear power plant, (iii) reprocessing of spent fuel, (iv) dismantling of the reactor and reprocessing plant (van Leeuwen, 1985). The causes of large divergence in the capital costs for the construction phase being unknown, it cannot be considered as a purely stochastic phenomenon (van Leeuwen, 1985). (f) Nöggerath et al, 2011. (g) Brumfiel, 2011a; 2011b; Funabashi and Kitazawa, 2012. (h) Specified as "the availability of nuclear, chemical, biological and radiological technologies and materials leads to crises" (WEF, 2013). (i) O'Connor, 1973; Stiglitz, 2011, see also Box 2.4.

comes possible to discuss the relevance and usefulness of representations of the nuclear energy system;

(2) order logic – 1st order and 2nd order. First-order sources refer to the cases where the source of risk can be treated as an independent cause (e.g. single-mode failure of a valve, terrorist attack, human error), whereas second-order sources refer to both cases where the failure results from a set of first-order sources (common-mode failure, e.g. a tsunami and an earthquake like at Fukushima) and cases where the source of risk itself refers to a complex-network of distinct causes (e.g. social costs in case of accident depend on a virtually infinite set of causes such as the number of people affected by the accident, which in turn depends on the cause(s) of the accident and the magnitude of the consequences both in space and time).

The frontier between *knowledge* and *ignorance* about nuclear power is not clear and actually is strongly debated. An overview of this debate is provided in box 2.2.

Box 2.2 The problem of contrasting knowledge claims about nuclear power: the case of low-level radiation.

Some of the risks involved with nuclear power are strongly debated on the basis that whether they should be considered as *knowledge* or as a source of *ignorance*. This is the case for instance of the effects of low-level radiation on health for which there exist contrasting knowledge claims:
(1) "we don't know the effects" (e.g. Brenner et al, 2003; Brenner, 2011);
(2) "we know the effects *and* they don't matter" (e.g. Upton et al, 1992; Cohen, 2002);
(3) "we know the effects *and* they are dangerous" (e.g. López Arnal and Rodríguez-Farré (eds.), 2008).

The following comment made on a Column in *Nature* (Brenner, 2011) nicely summarizes the scientific controversy over the effects on health from low-radiation:

"Dear Dr Brenner:
Reading the paper at <http://www.chembiodiv.ch/highlight.htm> will show that we know much about the outcome of extremely low-dose radiation on genetic material from nuclear plants that did not report any crash. If we don't believe to biological indicators and wait for data on humans only, it will be a long way before we can decide whether intact nuclear plants are safe. The genetic material of insects is different from our own, but the building blocks are the same, or is anyone aware that that of insects is a particularly labile genetic materials against radiations? Frankly I lack data about that.
All the best
Francesco Pietra
Member of the Editorial Board of "Chemistry&Biodiversity", I emphasize, though, that these are my personal views."

What we see from this discussion is that the problem associated with the scientific elicitation of low-level radiation on health may in fact reside in the difficulty to measure and quantify the effects of radiation at very low-levels on humans over a long period of time. That is, the effect of low-level radiation may rather refer to – and may be relevant to be considered as – a stochastic phenomenon (as suggested by the US EPA, 2012). As a matter of fact, low-level radiation should be considered as a situation of "indeterminacy" (as shown in fig. 2.5) where it is simply practically impossible to define the effects on health (the *type*) due to the magnitude of the error bars on every measurements (the *instances*) (e.g. Cohen, 2002; Brenner et al, 2003).

One of the consequences of this indeterminacy about low-level radiation is that there is not even an agreement on which methodology to use to address this problem (Butler, 2011). As a result, this further delays the research efforts to measure the long-term health effects of the nuclear accidents at Chernobyl, and as such further prevents from resolving this scientific controversy.

Another consequence of the stochastic phenomenon of low-level radiation is that since the adverse effects do exist on human but cannot be measured with enough accuracy, some observers claim that institutions responsible for assessing those effects are voluntary "purveyors of ignorance" (Ribault, 2013a; 2013b).

All in all, in the case of indeterminacy, a controversy results from which side of the Gaussian normal curve one focuses on. Then, as long as the contrasting *knowledge claims* do not reach a shared perception over the issue, it is impossible to formulate *scientific information* about the issue (shared representation). In return, contrasting knowledge claims further affect the problem of distrust from the public into the nuclear power industry relying on the perception of experts (see sect. 2.2.3).

Using the different sources of risk, uncertainty and ignorance from nuclear power identified in fig. 2.5, we can check the validity domain of conventional representations of nuclear power. In doing so we clearly see that both the deterministic and stochastic representations are incompatible with (1) the perception of risk in the general public; as well as (2) the complex nature of the "nuclear energy system" that goes beyond the nuclear reactor and the power plant:

(1) in relation to the conceptualization of risk – Fig. 2.5 shows that the situations of actual risk – in which information is available and reliable – is limited to the failure of the components or systems of components of the facilities for which the system behaves within the accessible state space (e.g. classic mechanics). However, this view

loses its validity as soon as the system interacts with other systems affected by uncertainty – for which there is doubt about the reliability of the probabilities – or ignorance – for which the system behaves in a non-accessible state space (see box 2.3).

Box 2.3 Example of how ignorance affects the nuclear energy system.

Since the 9/11 terrorist attacks in the U.S., there is a general agreement among risk experts that hazards from terrorism should be accounted for in safety design (e.g. Chaplin et al, 2002; Perrow, 2007). The immediate response from those working on safety design of nuclear power plants therefore has been to account for scenarios of accidental crashes of commercial planes on the reactor containment building of the nuclear power plant (until that date, only crash of military planes were included in the design). Yet, one is forced to recognize that there is not enough information available on the actual set of possible outcomes in case of terrorist attacks on a reactor. That is, the issue of terrorism against the "nuclear energy system" cannot be reduced to a mere problem over the probabilities of an assumed outcome coming from another situation (e.g. a crash of a commercial plane on a public building) implying a situation of uncertainty, but that we simply do not know enough about what the set of possible outcomes is (i.e. the possible failure-modes caused by terrorism) hence implying a situation of genuine ignorance. As a matter of fact, risk experts by considering one "envisioned" scenario out of a virtually infinite set of possible outcomes (with all the same cause labeled as "terrorist attacks") misunderstand the challenge posed by ignorance any time a new source of "risk" emerges from a given social context. That is, the emergence of new knowledge (i.e. the danger of terrorism is real) unavoidably creates new sources of genuine ignorance (i.e. how terrorism and the nuclear energy system interact between each other).

As we see from fig. 2.5, irreducible uncertainty and genuine ignorance are at work as soon as one considers the interactions of the facilities from the nuclear energy system with the "external world" (e.g. the Earth, humans, institutions), whereas its internal parts (e.g. power plant, reprocessing plant, waste storage facility) are assumed to be governed by deterministic laws for which the representation is valid.

(2) in relation to the complexity of the nuclear power-supply system – The conventional engineering perspective about nuclear power consists in a linear view focusing on the industrial processes and facilities. As such it does not need the concepts introduced by complex systems thinking (see Chap. 1). However, such approach loses

validity as soon as energy systems are discussed from a societal perspective where complex relations are at work. This is the case of any discussion about the viability and desirability of nuclear power in relation with other alternative energy sources. The complexity of the "nuclear energy system" is discussed more in details in sect. 2.3.1.

2.2.4 Implications for the governance of nuclear power

It is often said that nuclear safety follows a continuous "learning process" like it is the case of any other technology (e.g. Carroll, 1995; Carayannis, 1996; Roux-Dufort and Metais, 1999). Such a view consisting in an incremental strategy to enhance learning by "trials and errors" (Wildavsky, 2000) is similar of the spiral model used in software development (fig. 2.6a). This approach is considered as an effective strategy to deal with uncertainty:

> *"Because it is a discovery process that discloses latent errors so we can learn how to deal with them, trial and error also lowers risk by reducing the scope of unforeseen dangers. Trial and error samples the world of as yet unknown risks; by learning to cope with risks that become evident as the result of small-scale trial and error, we develop skills for dealing with whatever may come our way from the world of unknown risks."*
>
> (Wildavsky, 1988: 37)

Yet, such an improvement process that may be valid for software management and other fast-changing/low-stakes technologies does not seem applicable – nor desirable – in the case of the nuclear energy system being large-scale/high-stakes by default due to the following constraints:

(1) constraints in space – The nuclear industry is not capable of gathering the information required to perform actual iterations. In fact, although the history of nuclear power shows that the most important reactor accidents throughout its history have had different causes – leading to the idea of a "learning process" gathering new information – there exist sources of irreducible uncertainty and ignorance as nuclear safety deals with natural systems preventing it from closing each loop of a spiral-like model of improvement. That is, new information about a reactor accident (e.g. human errors matter since the reactor accident at Chernobyl) only apparently transfers

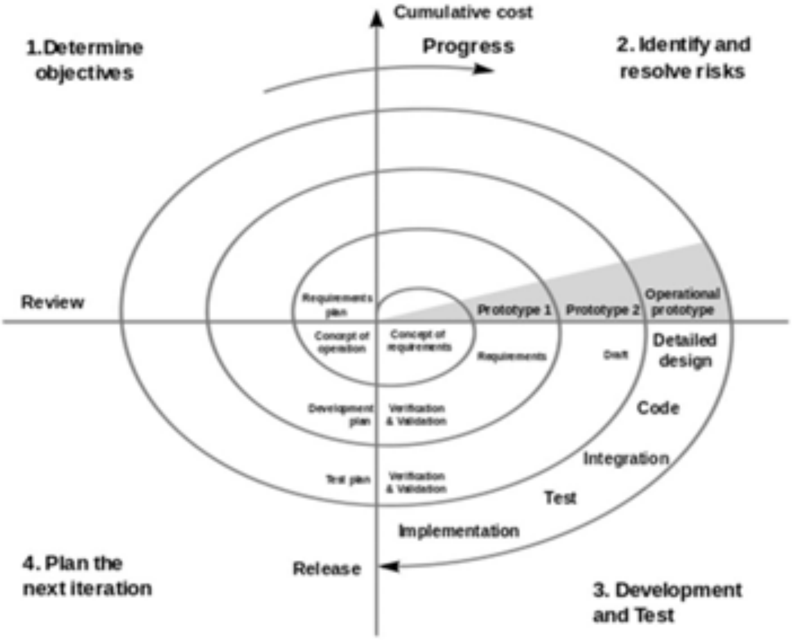
uncertainty to risk as there exist virtually infinite combinations of system and component failures caused by natural systems.

(2) constraints in time – Even in the case the nuclear industry would be able to improve continuously through a large-scale experiment, there is a striking incompatibility between the pace at which "new information" is generated – there happens one reactor accident every eight years on average in the world (Diaz-Maurin, 2011a) – and the pace at which this new information can be integrated in new safety designs and procedures (requiring about 10 years), and even worse, to be significantly deployed in actual new plants (requiring about 50 years for a whole generation of new plants to be deployed at large scale).

As a matter of facts, the nuclear safety can by no means be considered as improving

a.

Spiral model in software development
(after Boehm, 1988)



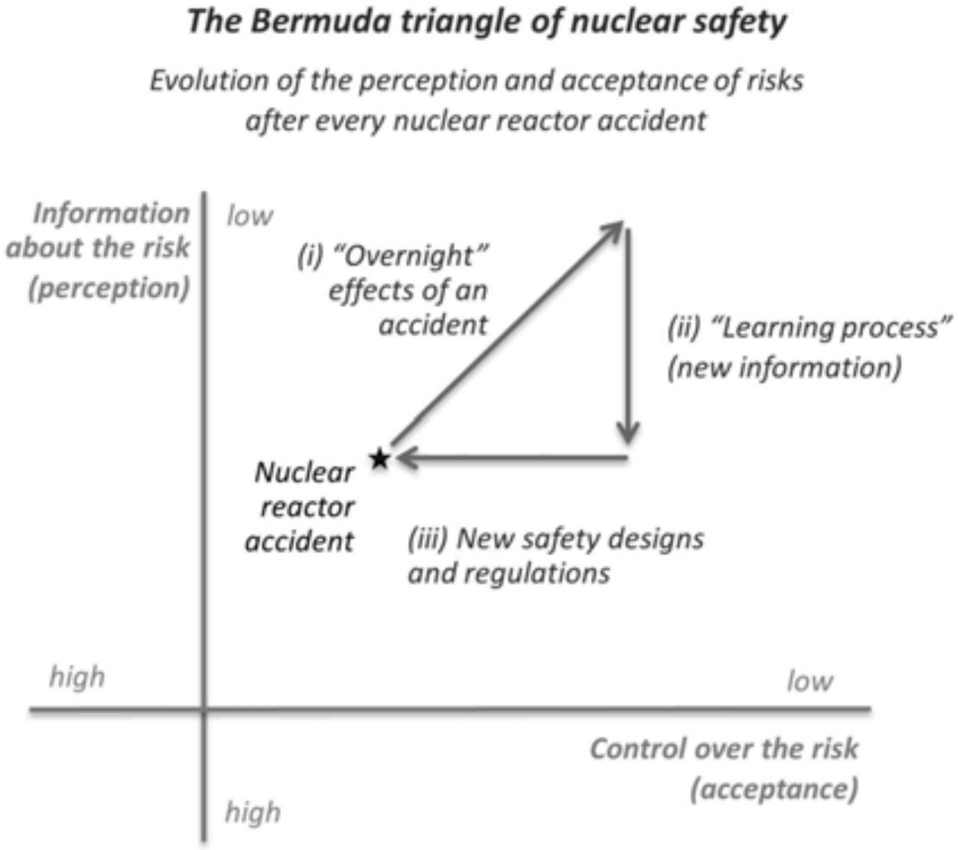
(Source: "Spiral_model_(Boehm,_1988).png" [Public domain],
via Wikimedia Commons)

Figure 2.6 Improvement process in software development versus the "Bermuda triangle" of the perception and acceptance of risks from nuclear power.

following the typical continuous learning process.

As discussed in sect. 2.2.2, when risk is perceived as being increasing, it becomes less accepted. In the case of nuclear power, given that (1) risk cannot be reduced due to the unavoidable existence of uncertainty and ignorance and that (2) accidents act as signals and cannot be avoided, in the long term risk is being perceived as increasing (Slovic, 1987). This refers back to the nuclear predicament discussed at the beginning of this chapter. That is, perceptions and acceptance over risks from nuclear power appear as entangled in a sort of "Bermuda triangle" as shown in fig. 2.6b. This Bermuda triangle acts as an 3-phase attractor over the perception and acceptance of risks from nuclear power: (1) first, a reactor accident makes nuclear power less accepted and less known in the immediate aftermaths; (2) then claims about its learning process by gathering new information from the accident makes it better

b.



"known"; and (3) finally, claims about the integration of those new information into new safety design and regulations makes risks from nuclear power more "accepted" until another accident happens.

As a matter of fact, the very nature of this complex technology where reactor accidents are unavoidable (Perrow, 1984; 2011; Pidgeon, 2011; Diaz-Maurin, 2011a) among other irreducible "risks", implies that nuclear power cannot but be chronically perceived as risky and remain controversial over time. In fact, any claims about the improvements in nuclear safety after each accident clash against the unavoidability of those accidents inherent to complex systems, hence self-sustaining the distrust between the industry and the public.

Going further, this attractor makes the acceptance of nuclear energy system affected by a "sword of Damocles" syndrome, a totally random phenomena which depends not on its internal characteristics but on the occurrence of externally-induced reactor accidents. At this stage, the "sword of Damocles" syndrome affecting nuclear safety poses the problem of the "ethics of gambling" – an expression suggested to me by Mario Giampietro – in relation to the governance of nuclear power. In fact, as observed by Giampietro (1994) in the discussion over the concept of *sustainable development*: "But even if we accept that gambling cannot be avoided (after all this is what life is about), we should at least be able to define the terms of the bet (what can be gained, what could be lost) and the rules of the game (who is calling the bet and who will pay for or gain by it); unfortunately, at present, these terms are anything but clear." (Giampietro, 1994: 624) This refers back to the metaphor of the "black swan" (Popper, 1959; Taleb, 2007) which poses the epistemological dilemma of dealing with the unavoidable existence of low probable events with high consequences, for which the reactor accidents at Fukushima are the most recent illustration in the case of nuclear power (Coderch, 2011).

The issue of gambling therefore applies also to the governance of nuclear power (box 2.4).

Box 2.4 The ethics of gambling with nuclear power

The systemic problems affecting the assessment of risk from nuclear power raise concerns about who wins and who pays from this technology. Indeed, in the same way whether nuclear energy is actually safe or not, it depends on how one look at the problem and, in the end, who one is asked.

Nuclear power is a highly subsidized energy source. Subsidies allow to reduce the cost of production of electricity from nuclear energy compensating for the costs of uranium, safety and liability, cooling water, waste management, plant dismantlement (Costanza et al, 2011). For instance, in the US, the still active "Price-Anderson" law of 1957 limits the liability for nuclear accidents to US$12.6-billion. By adopting these rules, it becomes relatively "cheap" to produce electricity from nuclear energy.

However, having electricity cheap to produce for the energy provider company does not necessarily means that the overall cost related to nuclear energy system as a whole remains low from a societal point of view. For instance, the costs of the nuclear accidents at Fukushima in Japan provide us with a good example about the limits of this idea of cheap nuclear energy. Indeed, the total cost of the natural disaster in Japan has been estimated to US$ 300-billion. However, the liability of TEPCO should be limited to between US$24-billion and US$45-billion (Reuters, 2011b). The irony is that, in Japan, the law of "Act on Compensation for Nuclear Damage" of 1961 does not include any liability for consequences of nuclear reactor accident after a natural disaster, so that the US$24-billion of liability from TEPCO has been the result of negotiations between the Japanese Government and the electricity provider, hence not constrained by any law.

Therefore, we see that from the total cost of the disasters in Japan (US$ 300-billion), a significant amount (still to be determined) will correspond to the nuclear accidents alone. So, the difference between this amount and the *negotiated* liability of TEPCO will be shared with the society. Now, if we add the fact that TEPCO would have to borrow some money from major banks of Japan, nuclear energy companies demonstrate a clear non-creditworthiness, where most of the costs in the end are transferred to the society.

Therefore, given the problems of evaluating the risk related to nuclear safety discussed above and the large financial crackdown that one nuclear accident can have on a nuclear energy company, one can ask why these companies keep taking such "risks". Part of the answer resides in the fact that in this "game", nuclear energy companies do not – and could not – play alone but clearly rely on the society to externalize the risk of some possible outcomes and especially in relation with adverse consequences affected by uncertainty. In this sense, one can speak of nuclear safety as being a sort of distorted casino game in which if *they* win, *they* take the cash and if *they* lose, *society* pays the debts.

As stated by Stiglitz (2011): “a system that socializes losses and privatizes gains is doomed to mismanage risk” – a problem that was already anticipated as early as the 1970s (O’Connor, 1973) – which, in return, leads to a distorted governance over its desirability.

Given this situation, the “Bermuda triangle” of risks explaining the chronic controversy of nuclear power (sect. 2.2.3) most probably is at the origin of the efforts being made by the nuclear industry in the recent years to shift from a narrative focusing on its *safety* – that is impossible to resolve – to a narrative focusing on its *sustainability* – by framing nuclear power as a “low-carbon” or even “carbon-free” and “renewable” in some cases (e.g. Deutch and Moniz, 2006; WNA, 2013) – for an more in-depth discussion of the narratives about nuclear power, see Chap. 6. Indeed, given that risks from nuclear power appear as being an unsolvable dilemma, efforts are now made in emphasizing on its benefits which have never been clear neither (Slovic, 1987) – Part 2 of this thesis provides a way to check those claims against socio-economic and environmental constraints. Indeed research has shown that risk and benefits are correlated, although acting in an inversely proportional way (Starr, 1969; Fischhoff et al, 1978). That is, if the benefits of a technology are perceived as increasing, its risks are then being perceived as decreasing. In return, a technology will appear as undesirable if being perceived at once as a low-benefit/high-risk technology.

This was the case of nuclear power for which as early as the 1970s – before any reactor accident ever happened – people were judging the benefits of this technology to be quite small and the risks to be unacceptably high (Slovic, 1987). Psychometric studies conducted shortly after the first worldwide reactor accident which happened on March 1979 at Three Mile Island in the US showed that the perception of risk was not significantly affected as nuclear power already was scoring highest relatively to other technologies and activities on the characteristics that make up the control-over-risk factor (Slovic, 1987). That is, early psychometric studies showed that risk from nuclear power used not to be accepted – in spite of its continued deployment highly subsidized by governments . . . – for the good reason that it was considered as “uncontrollable; dread; catastrophic potential; with fatal consequences; inequitable in the distribution of risk and benefits; affecting future generations; cannot be easily reduced; increasing; involuntary” under the characteristics affecting the acceptance of risk from a technology (see sect. 2.2.2).

Here it is interesting to note that the perception about the lack of control over the risk was relatively higher than perception about the availability of information about risk in the case of nuclear power. That is fear from nuclear power seems to come first from characteristics as regards to its control, while its risk are perceived as being relatively known. However, for the good reason that nuclear power inherently conveys irreducible uncertainties, so that risk cannot be *controlled*, nuclear power appears as being self-sustaining itself its systemic lack of desirability despite its risks are considered as better "known" relatively to other technologies.

The strategy of reducing the inequitable distribution of its risks and benefits by focusing on its benefits around sustainability and energy security was actually quite successful to the extent that, in the early 2000s, nuclear power started to appear as a more desirable energy source in some countries (e.g. Jenkins-Smith, 2011 in Slovic, 2012). Yet, those efforts have been laid to dust almost overnight after the three reactor accidents at Fukushima bringing back nuclear power as an undesirable technology. Risk from nuclear power was once again entangled in its Bermuda triangle.

In conclusion, the fact that governance of nuclear safety is relying only on quantitative assessments has two important epistemological implications: (1) the use of conventional quantitative risk assessment methods loses validity as soon as it attempts to deal with situations of uncertainty and ignorance where risk cannot be quantified; and (2) in return, reducing situations of uncertainty and ignorance to a set of outcomes and probabilities compatible with quantitative risk assessment methods implies the unavoidable result of a loss in legitimacy, since the pre-analytical choices over the perception of risk (definition of what the "acceptable risks" are) do not involve participation of the public. Therefore, the current situation in which the governance of risk from nuclear power relies exclusively on quantitative analysis, based itself on the unavoidably biased perception of the experts, translates into a systemic doubt about the relevance and usefulness of the representations used to deal with the desirability and viability of nuclear power.

2.2.5 The need for an alternative representation of nuclear power

The unavoidable existence of uncertainty and ignorance referring to *irreducible* (or non-quantifiable) risk in the case of nuclear power poses the question of which typology of representations is applicable in these situations. Here I provide a critical appraisal of the conventional representations of the nuclear energy system based on lessons from complex systems theory developed in Chap. 1. This justifies why it is crucial to adopt an alternative representation if we are serious about discussing the viability and desirability of nuclear power.

As discussed in sect. 2.2.1, the deterministic representation was originally used to assess the risk from nuclear power. However, in the case of the nuclear reactor such a representation was too simplistic as it requires that all possible outcomes and probabilities are known in advance, hence implying the nuclear reactor be considered as a purely mechanical system behaving within a known state space. Yet, the first nuclear reactor accident which happened at Three Mile Island in 1979 provided the striking evidence that the nuclear reactor may behave outside such a known state space. In other words, there are situations of uncertainty affecting the nuclear reactor for which the deterministic representation loses validity.

In their rush to address the obvious impossibility of knowing all possible outcomes, risk assessment experts rapidly generalized to nuclear safety design the rationale of acceptability of risk which was used so far in the aeronautics and space industries. This approach was turned into the formal discipline of probabilistic risk assessment (PRA) illustrated by the publication in 1975 of the famous WASH-1400 Report also known as the "Rasmussen report". The probabilistic approach to risk was introduced with the claim that it will be able to deal with "design under risk". However this approach requires a pre-analytical step consisting in the distinction between the outcomes that will be considered within the scope of analysis (accepted risks) and the ones that will be disregarded (rejected risks). As such the chosen set of outcomes under the analysis is setting the boundaries of the state space that makes it possible to improve the evaluation of the occurrence and consequences of *those* outcomes. That is the probabilistic approach ended up corresponding to a mere sophisticated evaluation of "risks under design" which clashed against the original purpose for which it was introduced. But the epistemological implications of adopting such approach were certainly not clear to the analysts at the time given that their criticisms as regard to the WASH-1400 report were only questioning the outcomes of the approach, not the methodology (e.g. Lewis et al., 1978; 1979).

In fact, there was a shared perception among risk analysts that the probabilistic approach was very useful for "delineating procedures through which quantitative estimates of the risk can be derived for those sequences for which a data base exists" (Lewis et al., 1979: 4688). Yet, the following statement should have alerted them on the possible existence of a systemic problem of methodology: “We are unable to determine whether the absolute probabilities of accident sequences in WASH-1400 are high or low, but we believe that the error bounds on those estimates are, in general, greatly understated. This is true in part because there is in many cases an inadequate data base, in part because of an inability to quantify common cause failures, and in part because of some questionable methodological and statistical procedures.” (Lewis et al., 1979: 4688). That is, the confidence in the use of *subjective probabilities* should have clashed against the impossibility of constituting the adequate data base required to estimate those probabilities, for the good reason of the unavoidable existence of an unknown possible state space. Therefore, the adoption of the probabilistic approach to the nuclear safety design corresponded to reduce the nuclear reactor to a purely stochastic system for which probabilities can be estimated (once the unknown possible states have been disregarded as “rejected risks” under the analysis). As such, however, the stochastic representation of the nuclear reactor was still unable to deal in practice with the irreducible uncertainties putting doubt on the information space, despite optimistic claims.

As we see, both the deterministic and stochastic representations used in the nuclear safety design refer to the same epistemological problem of applying quantitative risk assessment methods to systems affected by irreducible uncertainty and genuine ignorance. In fact, these uncertainty and ignorance were revealed in the case of nuclear power by the successive nuclear reactor accidents at Three Mile Island, Chernobyl and Fukushima, whose failure mode was each time different. Modeling the nuclear reactor using deterministic and stochastic representations is not satisfactory because the nuclear energy system inherently interacts with other systems that can cause initiating events. Among those systems are natural systems (e.g. human behavior, earthquakes, tsunami) for which it is not possible to know in advance all possible outcomes. In such situations where interactions with natural systems are at work, quantitative models cannot predict with accuracy what will happen in space and time when using a given technology. Even in the hypothetical case where there would be no doubt about the current information about those systems, quantitative models will lose their validity as soon as there is new available knowledge about a given natural system (e.g. historical data on earthquakes in a given region). For instance, this has been the case of the safety design of the Fukushima-Daiichi power plant for which new data on seismology was available – but not accounted for – before the Tohoku earthquake happened (Funabashi and Kitazawa, 2012). In addition, natural systems may also interact between each other. That is, there exist feedback relationships between various natural systems that make conventional representations unsatisfactory. In fact, some risk assessment experts (e.g. Leveson, 2012) already acknowledge that the chain-of-event conception of accidents typically used in conventional risk assessment methods cannot account for the indirect, non-linear, and feedback relationships which characterize accidents typical of complex systems (Perrow, 1984). More generally, since natural systems imply unavoidable ignorance by nature and in their interactions some of the complex relationships between natural systems having potential significant effects on the nuclear reactor will always remain unknown. This implies that the nuclear power-supply system faces unavoidable sources of ignorance when exposed to possible external initiating events (e.g. earthquakes, tsunami) with unknown interactions (common-mode failures). Complex systems theory tells us that the presence of feedback relations makes it impossible to predict all possible outcomes due to the unavoidable existence of emergent properties.

This demonstrates the relevance of considering the overall nuclear energy system and its interactions with natural systems as a self-modifying system (see Chap. 1) for which sources of uncertainty and ignorance potentially affect its safety. That is, as soon as a system deals with other systems that are of a different nature, it makes the system at stake inheriting from this nature, i.e. behaving according to these characteristics. For instance, the fact that the nuclear reactor interacts with natural systems makes the *nuclear energy system* a self-modifying system for which it is unavoidable to discuss possible sources of uncertainty and ignorance, in addition of situations of risk. In other words, when dealing with risk, it is crucial that the worst situations of risk affecting a system – be it coming from another system – determines the choice over the representation used to deal with this system. Then, given that risk, uncertainty and ignorance act at different levels of the system, scales matter when discussing risk from the nuclear energy system. A satisfactory approach to risk must therefore be able to deal with the multiple scales. For this reason, since natural systems can be successfully represented using a complex systems approach taking into account their characteristics of complex relations and self-organization (see Chap. 1), it may be useful to adopt such a view when representing the nuclear energy system.

Moreover, as claims in favor of further deployment of nuclear power are now made about its sustainability in relation to energy supply issues, it may be even more relevant to adopt a complex systems approach as an alternative representation of the nuclear energy system, given that quantifying sustainability requires dealing with multiple scales (see Chap. 1).

2.3 Toward an alternative representation of the "nuclear energy system"

The lesson learned from the previous section is that there is a crucial difference between "what the system is" and "what the *representation* of a system is". This means that the pre-analytical choices over the models used to represent a given system *per se* do not carry information about the nature of the system itself nor about how it behaves. By adopting a given model, it implies an unavoidable loss on some of the characteristics of the system. This is what makes all models *wrong*. For this reason the question then is whether some can be *useful* to address a given question (Box and Draper, 1987). In the case of nuclear safety, using either deterministic or probabilistic models to assess risks implicitly considers that the system "is" either deterministic or stochastic while it is clearly not the case. As indicated above, risk depends on various factors that may be external to the reactor. A sound discussion over risk therefore requires looking at all the processes required to generate electricity using nuclear energy. This requires extending the boundaries of the representation from the nuclear reactor to the "nuclear energy system" as a whole. In addition, it requires dealing with the internal relations among its compartments.

In the end, building an alternative representation of the nuclear energy system requires shifting from a *structuralism* view to a *metabolic* view of the system. In this section, I attempt to define "what the nuclear energy system is" and "what it does" using a complex systems reading based on an assessment of the different possible perceptions over its structures and functions. Then, I present how those non-equivalent perceptions can be bridged in order to assess the viability and desirability of nuclear power.

2.3.1 Perceiving the complexity of nuclear power

As discussed in Chap. 1, the complexity of a system resides in the possibility to discern various subsystems that depends on the choices made by the observer as far as how to interact with the system. These subsystems correspond to the different possible scales at which the system can be perceived. These can be found either in space or in time.

To understand the importance of keeping separated these scales at all time in the analysis, we can look at the implications of confusing them when trying to define the nuclear energy system (see box 2.5).

Box 2.5 Example of the confusion of scales: "the nuclear industry is like the car industry"

To illustrate the implications of confusing the different scales involved with the nuclear energy system, I use the example of an article published in *Science* one month after the beginning of the nuclear crisis at Fukushima. In this article, Clery (2011) quotes Andrew Sherry, director of the Dalton Nuclear Institute at the University of Manchester, U.K., who "likens the differences [between nuclear reactors] to those between a car built during the 1960s and a car built today." Using such an analogy makes one think that the nuclear industry behaves and evolves similarly to the car industry. In short, they claim that the nuclear industry is like the car industry. Yet, this view carries some misconceptions and confusions about what the nuclear energy system is, both in space and time.

(i) in relation to space scale – Contrary to many other technologies, nuclear energy for the production of electricity cannot be experimented in a laboratory. Indeed, there is no "crash-tests" with nuclear power and simulations of accident scenarios will always be limited by our ability to imagine such situations based on the knowledge available at the time. For those reasons, nuclear power cannot but significantly exist by means of a large-scale deployment of reactors and other related facilities. Large-scale because the experience from the operation of nuclear reactors in one country is claimed to benefit the overall industry. But the contrary applies too. When an accident happens at one nuclear reactor, it potentially affects the entire nuclear industry (e.g. Fairley, 2011). The nuclear disaster at Fukushima demonstrated the global consequences not only on the environment and on humans[25], but on the debate about nuclear energy as well (Levi, 2011). This large-scale experiment of nuclear power suggests the existence of a

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[25] The accidents at the Fukushima-Daiichi nuclear power plant were rated at level 7 on April 11, 2011 (equaling the Chernobyl disaster at the highest level on the International Nuclear and Radiological Event Scale), one month after the beginning of the nuclear crisis (Reuters, 2011a). Level 7 considers the situation as a *major accident* with "major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures." (OECD/IAEA, 2009).

large-scale learning process. Yet, as discussed in sect. 2.2.4, the concept of incremental learning process is not applicable to the nuclear energy system for the good reason that accidents cannot be anticipated in the case of complex systems. That is, even if society would "accept [that] there will be events that will overwhelm [the] systems" (Michael Golay of the Massachusetts Institute of Technology in Cambridge quoted in Clery, 2011), the problem would remain in the ability of scientists to imagine such sequences of events simply because you cannot know much about the potentially adverse interactions between the nuclear reactor and the natural systems.

This misconception as far as how the nuclear energy system behaves comes from a confusion in space scale consisting in reducing the overall nuclear energy system to the size and characteristics of the nuclear reactor.

(ii) in relation to time scale – If one hardly finds today running cars dating from the 1960s (except the "classic cars"), the average age of the operating nuclear reactors worldwide is about 30 years (Schneider, 2008). So, when looking at the current fleet of nuclear reactors, we deal with designs dating from the beginning of the 1970s since at least a period of 5 to 10 years must be added for the construction and the development phase during which the safety assumptions have been taken. Yet, it is often claimed that "new nuclear power plants may not have failed in Japan" (e.g. Bullis, 2011). Such claims refer to new advanced reactors of generation-III+ that are safer *by design* compared with the old reactors. One famous illustration is the declaration of former French President, Nicolas Sarkozy on 11 March 2011 – the very same day the nuclear crisis started at Fukushima – where he referred to the safety design of the new AREVA EPR reactor (the French flagship generation III+ reactor design) by stating that the double wall structure would resist to a Boeing 747 crashes on the plant so that the reactor would not be damaged (*Liberation*, 14 March 2011). In fact, that is true. The double wall structure of the EPR reactor building would "according to the safety design" stand such an event as being part of the new safety features of the *future* nuclear EPR reactor. Yet – at the time of writing this thesis – there is still no EPR reactor operating in the world. In fact, since I was born (30 years ago), the electricity I have been consuming in France, in Spain and in the U.S. came only from generation-I and generation-II reactors (the first generation-III reactors – not III+ – being mostly located in Japan). Currently, only five EPR reactors are under construction worldwide, whereas the first one in Finland being built since 2009 may face more than six years delay with a starting operation now scheduled for 2015 . . .

Therefore, letting alone once again the confusion of space scale, such claims about better safety design make a confusion of time scale which consists in reducing the becoming of the overall nuclear energy system to the pace at which safety design of the reactor improves.

From box 2.5 we see that the existence of non-equivalent space and time scales at which the nuclear energy system can be perceived entail that their corresponding representations are incommensurable. For this reasons, it is crucial to bear in mind which scales is considered in an analysis (boundary conditions and time horizons) as they vary depending on the purpose of the analysis.

(1) The multiple perceptions in space

In the case of nuclear power, there are two main non-equivalent scales at which the nuclear energy system can be perceived:

(i) at the level of the processes (inside view, triadic reading: level n/n-1/n-2)

At this level, the nuclear energy system (level n) is defined by means of the interactions of its four standard unit operations required to generate electricity (focal level n-1) with their subparts in charge of each standard unit operation from the inside (interface level n-1/n-2) and with the whole nuclear energy system from the outside (interface level n/n-1). This perception corresponds to the interactions from inside the black-box of the nuclear energy system. It is useful for assessing and comparing the performance of energy systems generating the same energy carrier (e.g. electricity, heat or fuel), as it is further developed in chap. 3.

(ii) at the level of the energy supply sector (outside view, triadic reading: level n/n+1/n+2)

At this level, the nuclear energy system (level n) is defined by means of the interactions of the energy supply sector (at level n+1) with the different energy systems that compose from the inside (interface level n/n+1) and with the other compartments of society and the ecological processes (assumed to be stable boundary conditions over the time of analysis) from the outside (interface level n+1/n+2). This perception corresponds to the interactions from outside the black-box of the nuclear energy system. It is useful for assessing and comparing the viability and feasibility of energy systems in relation with the energetic metabolism of societies, as it is further developed in chap. 4.

These two non-equivalent perceptions of the nuclear energy system are illustrated in fig. 2.7.

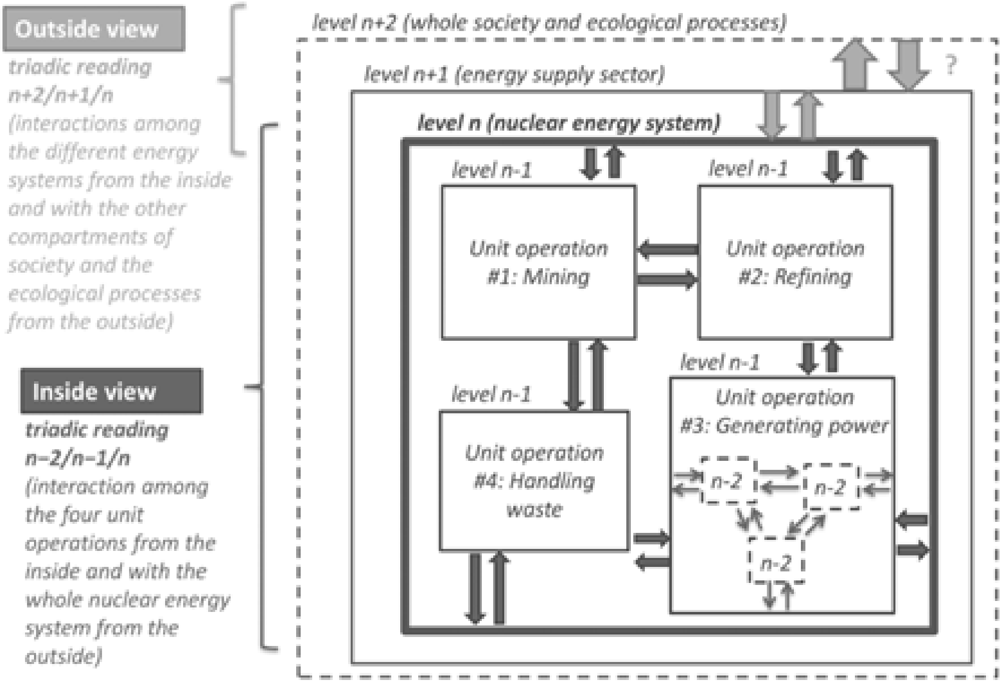

Figure 2.7 The various space scales of perception of nuclear power.

(2) The multiple perceptions in time

The time scale of a system corresponds to the speed at which one energy system operates and is subject to changes. Therefore, any representation of a system implying changes in speed requires a pre-analytical definition of a time scale for the domain used to describe changes in speed that defines: (i) the time differential (*grain*) – the time necessary to produce the output from the input within the process – in relation to (ii) the time horizon of the analysis (*extent*) (Giampietro et al, 2012). Using Georgescu-Roegen's (1971) flow-fund theoretical model, the grain refers to the generation and consumption of *flows* – elements disappearing and/or appearing over the duration of the representation – while the extent is related to the reproduction of *funds* – agents that are responsible for energy transformations and are able to preserve their identity over the duration of the representation. From this distinction, one can define the time horizon of the analysis which corresponds to the time scale necessary to cover the energy transformations occurring in time throughout the overall production process.

As for space scale, time scale is subject to contrasting perceptions for which there exist non-equivalent possible representations of the speed of an energy system. Two main perceptions can be considered when discussing the speed of the nuclear energy system depending on which typology of time one focus on:

(i) at the scale of the flows (grain) – This perception corresponds to the time scale at which the flows are generated (e.g. electricity, waste/pollution) and consumed (e.g. primary energy sources, production factors). By focusing on the *processes* generating flows, this perception makes it possible to define "what the system does". When dealing with energy systems generating energy carriers (e.g. electricity, fuels, heat), there exist multiple time scales at which the system can be perceived in relation to flows:

* at the scale of the *day* – perception useful when checking the performance of the system on the supply side in relation with the pattern of consumption of energy carriers on the demand side. This is especially useful in the case of power-supply systems generating electricity. This perception is not discussed within the scope of this thesis.

* at the scale of the *year* – perception useful when assessing the performance and viability of the system in relation with energetic metabolic pattern of society. This is the perception used in the assessments provided in Part 2.

* at the scale of *centuries/millennia* – perception corresponding to the long-term management of radioactive waste generated by the nuclear energy system over more than 100,000 years. Yet, this perception is impossible to be represented in practice due to the unavoidable "expiration date" of the validity of the modeling relations used in every representation, which is much shorter. That is, any attempt to deal with the handling of waste over the time scale that would be theoretically required would clash against the uncertainties involved. The long-term perception over the nuclear energy system therefore remains impossible to be represented in an analysis, implying the epistemological and ethical problems associated with the duties to the future generations (e.g. Shrader-Frechette, 2000). It must be noted that in such a situation, waste can no longer be considered as a flow but rather should be

perceived as a fund as their identity remains unchanged throughout the time horizon of the analysis. This applies even in the case where the time horizon of the analysis is driven by the reproduction of all the other funds.

(ii) at the scale of the reproduction of funds (extent) – This perception corresponds to the time required for the reproduction of the funds necessary for making and maintenance of the flows. By focusing on the *facilities*, this perception makes it possible to define “what the system is”. The time scale that must be considered when assessing an energy system corresponds to the envelope of the extents of the various facilities required in each one of the standard unit operations. Tab. 2.1 shows the orders of magnitude of the time required to reproduce the funds involved in the unit operations of the nuclear energy system (for a more detailed discussion about the standard unit operations of power-supply systems, see Chap. 3).

Table 2.1 Time required for the reproduction of funds of the nuclear energy system.

Unit operation	**Extent (order of magnitude)**
Construction (incl. R&D and licensing)	10 yr.
Power plant lifetime	35-40 yr.
Dismantling	10 yr.
Waste storage	10-30 yr.
Reprocessing (when applicable)	8-15 yr.
Waste disposal	100,000 yr.

Source: after Diaz-Maurin, 2011b.

We see from tab. 2.1 that the nuclear energy system can be perceived at different time scales that are non-equivalent to each other. When disregarding the issue of waste – something that has non-trivial implications for the governance of nuclear power . . . – the speed at which the nuclear energy system reproduces itself is in the order of magnitude of 70 to 100 years – which is in line with the time required for a transition of the overall nuclear-fuel cycle indicated by a MIT study (Kazimi et al., 2011).

It should be noted that the time scales – both grain and extent – differ from one energy system to another making the comparison more difficult unless one clearly specifies the pre-analytical choice in relation to time scale so that the validity domain of the analysis can be assessed. The ignorance of the non-equivalence of (space-)time scales involved when looking at the fund elements of the nuclear energy system – forcing the time horizon of the analysis – is at the origin of hasty judgments such as that nuclear power is a "carbon-free" energy source (see Chap. 6).

2.3.2 Representing the "nuclear energy system"

As seen in the previous section, the problem over the definition of "what the system is" and "what the system does" first and foremost refers to a problem of scale. That is, to every legitimate perceptions about the system can be attributed a specific scale of analysis and related boundary definition. The problem then comes from the fact that those perceptions are non-equivalent, implying that their corresponding representations are non-commensurable. As a matter of fact, any choice of scale entails a loss of potential information associated with the representations obtained using other scales. In return, a change in scale – i.e. in the narrative used to define what the system is and what it does – may significantly affect the pertinence of the representation.

Yet, from fig. 2.7, we see that the definition of "what the nuclear energy system is" depends on its interactions with its internal components from the inside and with its context from the outside. That is, both perceptions are useful for characterizing the nuclear energy system. In doing so, we define in fact an *holon* of nuclear power (see Chap. 6) that is a representation able to link together different perceptions of the system made at different scales in one set of production rules making it possible to discuss the internal viability and external feasibility of the system.

As a matter of fact, an alternative representation of the "nuclear energy system" must be able to deal with these two non-equivalent sets of space-time scales *at the same time*. In other words, a proper discussion over the viability and desirability of nuclear energy in relation with other alternative energy sources requires adopting a system of representation that is as complex as the system itself (Cilliers, 1998).

In addition to the issue of scale, discussing the viability and desirability of nuclear power requires dealing with multiple non-equivalent dimensions. Therefore, it is necessary to develop an analytical framework that makes it possible to deal with the complexity of this energy system characterized by *both* multiple scales and multiple dimensions of analysis. In fact, the analytical framework presented in Chap. 1 based on complex systems approach to energetics of human societies helps at doing this effort of integration that is then turned into practical procedures in Part 2.

2.4 Conclusion

The systemic controversy about nuclear power described in this chapter comes first and foremost from a misunderstanding of the issue of scales found both in scientific and public discourses. The existence of multiple scales at which the nuclear energy system can be represented refers to the unavoidable existence of multiple and non-equivalent perceptions of this technology. This 'social incommensurability' forces the analyst or commenter to deal with multiple scales both in space and time. The representation of nuclear energy based on a complex systems approach proposed in this chapter poses the foundations for a discussion about the viability and desirability of nuclear energy in a context of forced energy transition resulting from biophysical constraints (e.g. peak oil) and/or socio-economic constraints (e.g. economic slow-down).

However nuclear power cannot be taken as *desirable* and *viable* "by default". Deliberating over the desirability and viability of nuclear power requires participatory integrated assessments that must be able to deal with both the social incommensurability on the normative side, and the technical incommensurability on the descriptive side. When considering the normative side there is an obvious existence of different social actors – different potential story-tellers – expressing non-equivalent but legitimate perceptions of the same issue based on their values, beliefs, goals. The unavoidable existence of a "social incommensurability" associated with the "desirability" of nuclear power implies that any decision inherently generates winners and losers. Nevertheless, this epistemological challenge does not imply that quantitative analyses are useless. In fact, no matter what the values held by social actors are, there are key pieces of information required on the descriptive side: What are the factors to consider for studying viability? What are the technical coefficients of possible options? What are the biophysical costs? What about uncertainty?

Without this leap forward guaranteeing the quality of the assessment both on descriptive and normative sides, the decision-making process will continue to create frustration among concerned social groups. Indeed, the existence of contrasting perceptions over risk and sustainability makes 'truth' as an obsolete concept when using science for the governance of nuclear power. In such situations, scientific discussion serving governance purposes must shift from “truth” to “quality” (Funtowicz and Ravetz, 1993). That is, any quantification or deliberation implicitly requires a pre-analytical (arbitrary) choice of a given perception of the problem. This implies revisiting the role of the scientist when using science for governance. That is, in such situations, the scientific community must help to improve the quality and preserve the transparency of the information which the decision-making process is based on. Specifically, science and scientists should accept to return to be considered as another category of social actors rather than pretending to be referees above partisan interests. Moreover, Participatory Integrated Assessment requires mixing quantitative analysis to qualitative analysis. In this iterative process, natural scientists, generating the information space on the descriptive side therefore have to work together with social scientists individuating valid narratives and relevant attributes of performance to be used for the formalization of the assessment. This process, however, requires new procedures and new protocols developed to achieve such a result. Indeed, the conventional representations of nuclear power are not able to address the social and technical incommensurabilities. If we want to be serious about assessing the viability and desirability of nuclear power, it is crucial to adopt an alternative view. An attempt to build an integrated set of procedures making it possible to deliberate over the viability and desirability of alternative energy sources across scales is provided in Part 2.

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Part 2

Alternative procedures in energy analysis

Chapter 3

Assessing the viability and desirability of energy systems*

This chapter provides the practical aspects to be addressed when applying the Multi-Scale Integrated Analysis of Societal and Ecosystem (MuSIASEM) approach to energy supply issues. In fact, building upon the toolkit of “complex energetics” presented in Chap. 1, MuSIASEM is an innovative approach to accounting able to integrate quantitative information generated by distinct types of conventional models based on different dimensions and scales of analysis (section 3.1). As such, MuSIASEM can be employed for diagnostic as well as for simulation purposes. Section 3.2 presents the procedures required to characterize the existing energetic metabolism of socio-economic systems (diagnostic tool). Then, section 3.3 provides the procedures required to perform a feasibility–viability–desirability check of proposed scenarios in relation to energy transitions (simulator tool). When adopting this set of procedures, it becomes possible to check the *quality* of alternative energy sources in relation to the energetic metabolic pattern of human societies.

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3.1 Methodological background

3.1.1 The MuSIASEM approach applied to energy supply issues

The Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM – originally proposed as MSIASM by Giampietro and Mayumi, 2000a; Giampietro and Mayumi (eds.), 2000b; 2001; Giampietro, 2003; Ramos-Martin et al., 2007; Giampietro et al., 2012) is an innovative approach to accounting that integrates quantitative information generated by distinct types of conventional models based on different dimensions and scales of analysis. It builds on several innovative concepts derived from Bioeconomics and Complex Systems Theory, such as the flow-fund model, multi-purpose grammars and impredicative loop analysis (for more details see Chap. 1). The application of these concepts allows the simultaneous use of technical, economic, social, demographic, and ecological variables in the analysis of the metabolic pattern of modern societies, even if these variables are defined within different dimensions of analysis and non-equivalent descriptive domains and refer to different hierarchical levels and scales.

In the particular case of the energy supply issues, MuSIASEM can be employed for diagnostic as well as for simulation purposes:

(1) As a diagnostic tool (for more details, see sect. 3.2) – The accounting system is used to characterize the existing energetic metabolic pattern of the socio-economic system under analysis by providing information on:

(i) Flows of energy (defined as *flow element*) for which we define the total requirement, the fraction for internal consumption, the losses, the degree of self-sufficiency (internal supply), and imports and exports; and

(ii) A series of flow/fund ratios characterizing the rate (per hour of human activity), density (per hectare of managed land) and intensity (per Watt of installed technical capital) across different scales (including the whole society and each one of the lower-level compartments defined in the accounting scheme, such as the various economic sectors). These ratios are then compared against reference values describing ‘typical’ socio-economic systems.

(2) As a simulator tool (for more details, see sect. 3.3) – The MuSIASEM provides a feasibility–viability–desirability check of proposed scenarios in relation to energy transitions. In fact, the approach allows us to:

(i) Check the *feasibility* of proposed scenarios by looking at the compatibility of the system with the boundary conditions. These external constraints are checked by comparing the required local flows to both the supply and sink side of the local interface with the environment. This analysis is obtained by characterizing the required energy flows (dictated by the internal characteristics of the socio-economic system) with GIS data. The MuSIASEM methodology uses an *environmental impact matrix* for this purpose;

(ii) Check the *viability* of proposed scenarios by looking at the congruence between the requirement and the supply of flows across different compartments. This check can be done at different scales after characterizing the rate (per hour) and the density (per hectare) of the various flows in the chosen scenarios. For example, data on consumption aggregated at the level of the whole society must result congruent with the technical coefficients (e.g. yields, productivity of production factors, requirement of specific processes) describing the supply at local scales. The MuSIASEM accounting method uses a *multi-level, multi-dimensional matrix* for this task and a so-called *SUDOKU strategy* to check the congruence of values across the different scales and dimensions of analysis;

(iii) Check the *desirability* of viable scenarios by comparing the resulting metabolic pattern (flow/fund ratios) at the level of end-uses (specific functions at the local scale, such as deployment of nuclear power generation, public transportation) to benchmark values of flow/fund ratios (expected features of the functions expressed) characteristic of given types of socio-economic systems. Deliberating over the desirability of metabolic patterns requires conducting a participatory process of decision making in order to deal with the problem of social incommensurability.

3.1.2 Toward a new 'protocol' of energy accounting

As indicated in Chap. 1, the MuSIASEM approach provides a toolkit able to deal with the energetics of complex systems, including human societies. This toolkit consists in the use of several analytical tools (multi-purpose grammars, impredicative loop analysis, dendrogram, multi-level/multi-dimension matrix) based on innovative theoretical concepts derived in various fields. Here I present the practical aspects to be addressed when applying the MuSIASEM approach to energy supply issues.

Applying the MuSIASEM approach to energy supply issues first and foremost consists in focusing on the hypercycle of exosomatic energy, which is key to the possibility of reproducing the set of functional and structural compartments making up modern societies. That is, by opening the black-box of the energy supply sector it becomes possible to assess the congruence of the characteristics of the parts in relation to the characteristics of the whole energy sector, that in turn must result compatible with the characteristics of the whole society. Then, it becomes possible to check the quality of alternative energy sources introduced into the existing mix of primary energy sources for the supply of energy carriers.

The application of the MuSIASEM approach to energy supply issues primarily deals with the different possible non-equivalent descriptive domains used to describe the energy flows referring to different hierarchical levels and scales. Note that although this protocol does not explicitly address the different other possible dimensions of analysis (referring to the analysis of other flows such as food, water, monetary) their information remains accessible by means of the multi-level/multi-dimension matrix presented in Chap. 1 (see Giampietro et al., in press).

That is, the energy protocol proposed in this chapter provides two sets of procedures of integrated assessment mapping:

(1) the non-equivalent forms of energy flow across different space scales (see sect. 3.2 and 3.3) – In particular, the protocol makes it possible: (i) to link non-equivalent forms of energy (primary energy sources, energy carriers, "end uses") across levels (societal compartments, from the supply side and from the demand side). This is performed by using a multi-purpose grammar applied to energy – coined here as 'energy grammar'; and (ii) to map those flows onto the allocation of the fund elements (human activity, power capacity, managed land) determining the size of functional compartments across levels (flow/funds ratios). On that respect, it should be noted that previous important developments in dealing with the non-equivalent forms of energy across scales were made by Giampietro and Mayumi (2009) as well as Sorman (2011; Sorman and Giampietro, 2011; Giampietro and Sorman, 2012), on top of which the protocol presented here has been initially developed. See also their joint work (Giampietro et al., 2010; 2012).

(2) the non-equivalent perceptions of power levels across different time scales (see sect. 3.4) – The protocol goes one step further in providing a way to address non-equivalent perceptions of power levels (the existence of fund elements – technical devices – capable of transforming energy flows per unit of time) over various time

scales of analysis referring either to the reproduction of energy flows or to the reproduction of funds.

3.1.3 The difference between 'procedure' and 'protocol'

At this stage, before going further into the details of the proposed methodology, we should specify what we mean with 'protocol'. In doing so, we can recall Albert Einstein's famous advice of "making everything as simple as possible, but not simpler". Indeed, when facing the social and technical incommensurabilities typical of the analysis of the energetics of human societies (see chap. 1), it is essential to learn how to combine together the semantic side and the formal side without (i) losing too much relevant information when making models; and *at the same time* (ii) introducing too much complicatedness in the models.

This refers back to the difference between 'procedure' and 'protocol' in science. In fact, according to the Merriam-Webster dictionary, a *protocol* is defined as "a detailed plan of a scientific or medical experiment, treatment, or procedure", whereas a *procedure* is defined as "a particular way of accomplishing something or of acting". *Procedure* and *protocol* oppose to each other in the same way *rules* (being arbitrary and specific) oppose to *laws* (being general) (Pattee, 1978). That is, a procedure is more flexible in semantic terms than a protocol (usually used in models trying to represent laws, but remaining inherently *wrong* in George Box's terms), and as such seems to be more appropriate for the application of the MuSIASEM approach to energy supply issues. As a matter of fact, whenever used in this chapter, the term "protocol" should be understood as "a set of procedures making possible to deal with different energy forms across multiple scales", and not as a semantically closed plan.

It must be noted that the "standard" energy grammar proposed here (see sect. 3.2.1) along with the set of production rules (procedures) explaining how it works (see sect. 3.2.2 to 3.2.4) seek to provide a general framework to deal with the energetics of human societies. However, it should not be considered as a strict protocol that would be exempt from the pre-analytical choices over the issue definition in semantic terms that must be specified in every application of integrated assessment.

3.2 Diagnosis analysis: Dealing with different energy forms across space scales

Before presenting the logic of the ‘energy grammar’ we have to recall that the accounting of energy is quite tricky and full of potential pitfalls (for a theoretical discussion of the problems encountered when dealing with the energetics of complex systems, see Chap. 1). An effective accounting for characterizing the energetic metabolism of a modern society has to integrate, depending on the task of the accounting, non-equivalent choices of categories according to the different perceptions used to represent the same process. When dealing with the energetics of human societies, the two main perceptions over energy flows entail two distinct typologies of accounting:

(1) using the perception from outside the society – when studying the interaction of the society with its environment (black-box/context) we have to adopt quantitative assessments that are not referring to direct measures of “quantities of energy carriers” consumed within the functional compartments of society (the inside view). Rather we have to use two assessments making it possible to establish a relation between: (i) what is required from the context – a set of *Primary Energy Sources* (either locally available or imported); and (ii) what is required by the funds making up the black-box using a generic assessment referring to a single category of accounting – a single number indicating the *Gross Energy Requirement*;

(2) using the perception from inside the society – when studying the dynamic between requirement and supply of energy carriers within the society (interaction of parts within the black-box) we have to use assessments of energy quantities that are referring to actual flows of energy carriers of different qualities – e.g. kWh or electricity, or MJ of fuels – consumed in “end uses”. These energy carriers are produced and consumed by the functional elements of the society (or imported). Therefore in order to describe the various relevant aspects of the metabolic pattern the grammar uses the following four categories: (i) *gross supply of energy carriers* (local production + imports); (ii) *net supply of energy carriers for “end uses” (in the dissipative part)*; (iii) *losses*; (iv) *fraction of energy carriers invested in the local production (internal consumption in the hypercycle – in the Energy and Mining sector)*.

These typologies of quantitative assessments should not be confused when accounting energy flows. In fact, it is essential to be aware that Joules are not all equal! The “meaning” of 1 joule depends on (and must specified by) the category to which the

Joule belongs. This fact is well known in economics. For example when accounting money flows in the budget of a company, 1 US$ of profit is not equal to 1 US$ of gross revenue! Accountants dealing with money flows use an integrated set of categories: gross revenues, fixed and circulating costs, profits, taxes. In the same way, to generate an effective energy analysis it is necessary to use an integrated set of categories (as shown in fig. 3.1) and not using just a single generic category Joules "one size fits all" as unfortunately done in many applications of energy analysis. The energy analyst should always be able to answer the question "Joules of what"?

3.2.1 The 'energy grammar'

To better explain the two typologies of quantitative assessments required when dealing with the energetics of human societies, we use a graphical representation of an 'energy grammar' that makes it possible to link semantic and formal categories used for the accounting of energy flows in the metabolic pattern (see fig. 3.1).

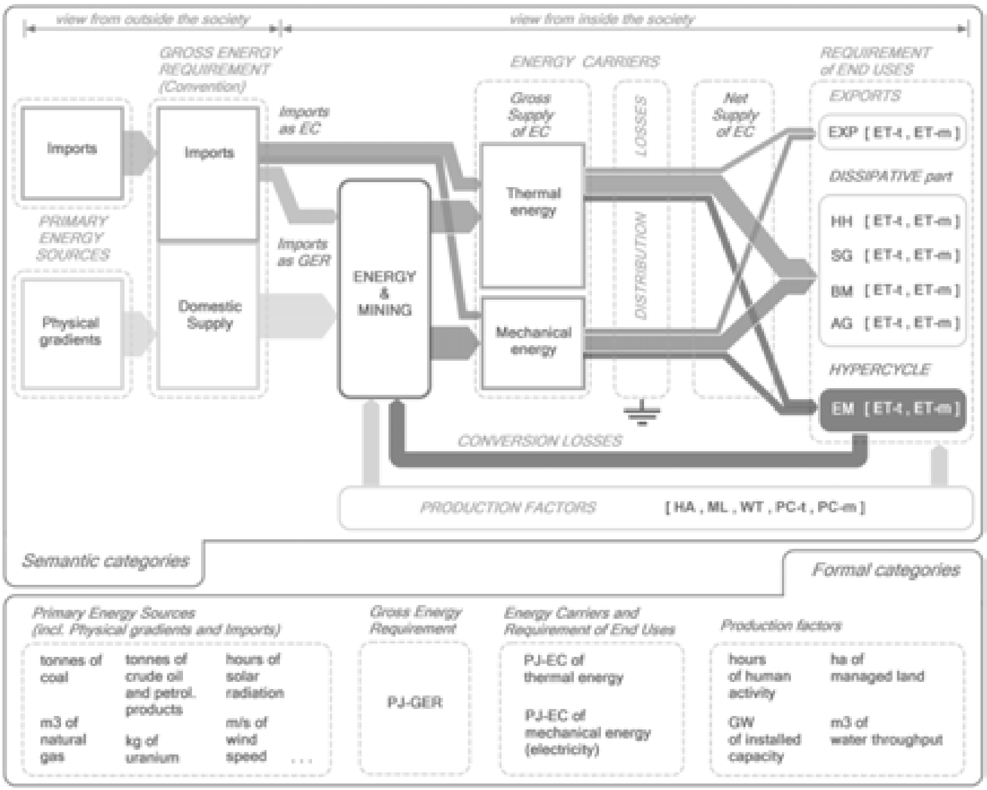

Figure 3.1 The "standard" energy grammar used for assessing the energetics of human societies – Relation between semantic categories and formal categories used for the accounting of energy flows in the metabolic pattern.

At this stage it is necessary to describe more in details the various categories used to characterize energy flows in relation to their position on the graph in the 'energy grammar':

(1) Perception from outside the society (on the left of the graph) *– Quantitative assessments relevant for studying the interaction of the society with its environment (black-box/context). These data are not referring to direct measures of quantities of energy carriers.*

(i) Primary Energy Sources (PES) locally available and Imports (assessing the requirement from the context) – quantitative assessments belonging to this category refer to physical gradients expressed in biophysical units (but not in energy units) – e.g. tons of coal, cubic meter of gas, tons of uranium, mass and speed of either blowing wind or falling water, intensity of sun radiation, tons of biomass. These primary energy sources are needed since they make it possible to produce energy carriers. To help studying the relation between the requirement of resources from the context (outside view) and the requirement of energy carriers inside the black-box) the quantitative assessment of Primary Energy Sources should be done in biophysical quantities. In fact, the role of the information provided by the assessment of PES is to indicate the requirement of favorable gradients (e.g. stocks of quantities of fossil energy materials, waterfalls, sun radiation, productive land, soil, water) which must be available, in order to be able to produce an adequate supply of energy carriers. This information is needed to calculate: (i) the limits determined by the availability of natural resources on the supply side – to assess external constraints to the gross supply; and (ii) the requirement of production factors (labor, technical capital, other inputs) which must be invested in the energy and mining sector for such a production – to assess internal constraints to the gross supply. In alternative to the exploitation of accessible natural resources for generating a supply of energy carriers a society must have the possibility of importing the required quantity of Primary energy sources or energy carriers. These two categories of accounting – referring to both PES and Imports – are indicated on the left upper part of the graphical representation of the energy grammar (fig. 3.1).

(ii) Gross Energy Requirements (GER) expressed in Joules of thermal equivalent (providing a coarse assessment of the energy requirement of the black-box) – this category refers to a virtual quantity of thermal energy that is calculated starting from five different pieces of information: (i) the mix of energy carriers required as net supply by the "end uses" of the various compartments; (ii) the choice of accounting rules used to convert assessment referring to Joules of electricity into assessments referring to Joules of thermal energy (the two quantities are not equivalent and cannot be summed as such); (iii) the mix of Primary Energy Sources; (iv) the characteristics of the various processes of conversions (Primary Energy Source – Energy Carriers); and (v) distribution losses in the energy sector. In existing statistics, the heterogeneous information carried out by these 5 items is collapsed into a single number – an overall assessment of Joules of Gross Energy Requirement, that is at times expressed using a category of reference such as Tons of Oil Equivalent (1 TOE = 42 GJ of GER thermal). This assessment (number) of Joules of GER does not refer to any actual flow of energy going through the society. Rather this assessment should be considered as a generic conventional assessment having the goal to compare in a standardized way different levels of energy consumption (both in quantity and quality) associated with human activity when comparing different countries. That is, we have to use a generic definition of "energy" – the perception from the outside – in order to be able to compare the energy consumption of different countries. Exactly for this reason this assessment must ignore the specific characteristics of the metabolic pattern as seen from the inside (see below). As a matter of fact, there is not even an agreed protocol on how to calculate this assessment. For example the energy statistics of British Petroleum (a historic pioneer in this field) or of the U.S. Energy Information Administration adopt a protocol to account for electricity, that is different from the one used by Eurostat or the U.N. Statistics (Giampietro et al., 2012; Giampietro and Sorman, 2012; Sorman, 2011). This fact shows why a single number assessing in generic way the "energy consumption" of the black-box is too coarse to be used to study and describe the processes of energy conversion taking place within the black-box.

(2) Perception from inside the society (on the right of the graph) *– Quantitative assessments of energy forms relevant for studying the dynamic between requirement and supply of energy carriers within the society (interaction of parts within the black-box). These data are referring to actual flows of energy carriers of different quality – e.g. electricity vs. fuels.*

(iii) Gross Supply of Energy Carriers (GSEC) – the gross supply of energy carriers (e.g. electricity, fuels, heat) corresponds to the supply of energy carriers actually made available to the society by the energy sector and by imports. This supply consists in a mix of energy carriers belonging to the categories of thermal energy (heat and fuels) and mechanical energy (electricity)[26]. Because these two forms of energy are non-equivalent, it is impossible to collapse or sum these two assessments into a single number at this stage. Clearly, it is possible to define an equivalent between 1 J of electricity (mechanical energy) and 1 J of fuel (thermal energy) using a conversion factor (e.g. 1 J of electricity = 2.65 J of thermal energy), but then this assessment would belong to the category of Gross Energy Requirement and it would no longer refer to the category of Energy Carriers, hence losing its ability to deal with an assessment of requirement and supply of energy carriers within the society. For this reason the Joules of energy carriers belonging to the category of mechanical energy cannot be summed to the Joules of energy carriers belonging to the category of thermal energy. To avoid this conundrum our grammar uses vectors (rather than individual numbers) to characterize flows of different types of energy carriers. For example a given flow composed by a mix of energy carriers can be described as X_{elec}, X_{fuel}, X_{heat} (with the three elements specifying the mix of quantities of different types of energy carriers) – or in alternative the overall flow of energy carriers can be specified in relation to two different types of energy – e.g. $X_{mechanical}$, $X_{thermal}$.

(iv) Net Supply of Energy Carriers (NSEC) – the net supply of energy carriers (characterized using a vector) is defined as the amount of the energy carriers of different

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[26] Here it shall be noted that the consideration of Energy Carriers followed throughout the present thesis is performed in relation with the converters within the energy supply sector (supply-side view), whereas Sorman (2011) considers Energy Carriers in relation with the End Uses within the energetic metabolism of society (consumption-side view). This implies a different semantic definition over what should be considered under the label “Energy Carrier”. For instance, in the present work adopting the view “from the energy supply sector”, the converters attached to this sector are said to *generate* Energy Carriers in the form of Mechanical Energy (electricity) and Thermal Energy, hence collapsing fuels and heat into Thermal Energy as well as not providing information about fuels. On the other hand, in the work of Sorman (2011) adopting the view “from the energetic metabolic pattern of society”, the converters attached to the End Uses are said to *consume* Energy Carriers in the form of Heat, Fuels and Electricity, hence not making the confusion between mechanical energy (motion) and electricity (vis electrica). Whereas the two views are correct in relation to their goal – supply-to-demand bridge using a bottom-up approach in the present case, and demand-to-supply bridge using a top-down approach in Sorman (2011) – further work should be done to address in a systemic way the different legitimate perceptions over the definition of “converters” and “Energy Carriers”. A suggestion could be that the term Energy Carriers may refer only to the energy forms generated by the converters attached to the energy supply sector (e.g. power plants, refineries), whereas the energy forms referring to End Uses may only be expressed in relation to *societal functions* (e.g. moving goods, heating houses, building roads). For a discussion, see Giampietro and Sorman, 2012.

types required by the set of functional compartments of the society (including exports) in a given mix. The overall vector of aggregate consumption (referring to the whole society, defined at level n) is defined by a matrix of vectors. Each vector defines the pattern of consumption of each one of the compartments inside the dissipative part and exports, in relation to processes taking place within the society at level n-i. Using a vectorial representation NSEC is equal to the GSEC minus the vector of DISTRIBUTION losses.

(v) Characterization of "End Uses" – the grammar represents on the right side the five standard functional compartments making up the society, as well as the EXPORTS whose energy carriers are actually consumed outside the system. The five functional compartments can be divided into two groups:

(1) DISSIPATIVE part – including four functional compartments that are consuming energy carriers: HH (household sector – having the goal of reproducing human activity), SG (Service and Government – having the goal of reproducing institutions and carrying out transaction activities), BM (Building and Manufacturing – having the goal of producing goods, technical capital and infrastructures), AG (Agriculture – having the goal of producing food). The pattern of consumption is described using four vectors defining the characteristics of "End Uses".

(2) HYPERCYCLIC part – made-up by the only sector that generates more energy carriers than it consumes – EM (Energy and Mining). The pattern of consumption of EM is also described using a single vector defining the characteristics of "End Uses". The HYPERCYCLIC part corresponds to the CONVERSION losses that are the investment of energy carriers required to generate the GSEC – letting alone the investment of other production factors.

An important observation is due in relation to this characterization of the end uses. For each one of the six compartments, the vectors used in the energy accounting system include different pieces of information referring to:

(i) energy flows (on the right side): type and amount of energy carriers (EC) – e.g. Joules of thermal energy (fuel and heat – ET_t) and Joules of mechanical energy (electricity – ET_m);

(ii) production factors (from the bottom): (1) amount of human activity (HA, expressed in hours of human activity per year in the compartment providing the required control to the generation of useful energy); (2) amount of managed land (ML, expressed in hectares of managed land); (3) amount of water throughput (WT, expressed in cubic meters of water throughput); and (4) type and amount of power capacity (PC) expressed in GW of installed capacity (e.g. GW of PC converting fuels and heat – PC_t – and GW of PC converting electricity – PC_m).

These vectors highlight the characteristics (both quantitative and qualitative) of the demand side in relation to energy security. In fact, when adopting this representation, we can see that the various sectors do not just consume "energy", but an expected mix of quantities of energy of different types (thermal and mechanical) at given levels of power (they require a mix of power capacity) and land used (e.g. cropland for biofuels), requiring a given amount of human activity providing control on the conversions (e.g. labor requirement) and water consumption (e.g. for irrigation, cooling system) associated with the control of technical devices.

(vi) Requirement of End Uses Dissipative (REUD) – the energy requirements of the dissipative part for "end uses" are defined by the amount of energy carriers (described by a set of vectors) consumed by those final compartments included in the DISSIPATIVE part. When dealing with the metabolic pattern of energy consumption inside the system, the DISSIPATIVE part includes all the compartments of society (HH, SG, BM, AG) minus the Energy and Mining (EM) sector. It should be noted that the ultimate goal of socio-economic systems – like all living systems – is guaranteeing its reproduction and allowing its development (qualitative change). This is done by increasing as much as possible the fraction of consumption of energy carriers and production factors in the dissipative compartment – final consumption, services and government, building and manufacturing and food security.

Coming to the quantification of energy flows – keeping production factors apart – when adopting a vectorial representation REUD (a matrix with 4 rows) is equal to NSEC (a matrix with 5 rows, when excluding EXPORTS) minus the vector describing the pattern of consumption of energy carriers within the Energy and Mining sector (vEM). These matrices and the vector vEM are described on the right of the graph in fig. 3.1.

3.2.2 The formal relations of energy flows

Using a formal representation of energy flows based on matrices and vectors, the energy grammar can be summarized by a set of formal relations (keeping the production factors apart):

(i) referring to the external view:

$$GER_i = (GER/GSEC)_j \times GSEC_{i,j} \qquad \text{eq. (3.1)}$$

where:
i – corresponds to the different Primary Energy Sources making up the Energy and Mining sector;
j – corresponds to the Energy Carriers (thermal and mechanical).
This formal relation links Energy Carriers (expressed in J-EC) to Primary Energy Sources (expressed in J-GER) on the supply side.

(ii) referring to the internal view:

$$GSEC_{k,j} = REUD_{k,j} + HYPERCYCLE_{k,j} + LOSSES_{k,j} + EXPORTS_{k,j} \qquad \text{eq. (3.2)}$$

where:
k – corresponds to the different End Uses making up the Whole Society (level n).
This formal relation links End Uses (measured in J-EC) to Energy Carriers (expressed in J-EC) on the consumption side.

(iii) bridging the external and internal views:

$$(PES/EU)_{i,k} = (GSEC/TGSEC)_{i,j} \times (ET/TET)_{j,k} \qquad \text{eq. (3.3)}$$

where:
$(\mathrm{GSEC/TGSEC})_{\mathrm{i,j}}$ – corresponds to the proportion of EC j (thermal or mechanical) generated by each PES i (external view);
$(\mathrm{ET/TET})_{\mathrm{j,k}}$ – corresponds to the mix of EU k (REUD, HYPERCYCLE, LOSSES, EXPORTS) that consume each EC j (internal view).
This formal relation makes it possible to link Primary Energy Sources to End Uses by mapping (1) the supply of EC j generated by every PES i to (2) the consumption of EC j by every EU k. This relation disregards the existence of possible specific PES-to-EU relationships (e.g. coal-fired power plants used only for industry, imports of specific petroleum products for the airline industry, etc.).

By using this set of formal relations of different energy flows across dimensions is useful to characterize in a synthetic way the energetic metabolism of society. In particular, it generates information about (1) the profile of consumption of primary energy sources, (2) the profile of production of energy carriers, and (3) the profile of consumption of energy carriers among the different end uses. As seen in Chap. 3, this formal representation implies a quantitative closure of the pattern of consumption and production of energy flows going through the society (GSEC must be equal to the sum of the energy throughput allocated to the DISSIPATIVE part, the HYPERCYCLIC part, or the EXPORTS – energy flows cannot disappear from the accounting system!). That way it makes it possible to eventually generate missing information by deduction. This is also called the mosaic effect across scales (Giampietro, 2003; Giampietro and Mayumi, 2009; Giampietro et al., 2012). An application of these formal relations is provided in Chap. 5 for the case of South Africa.

However, these formal relations do not carry information about the profile of investment of other production factors in the different compartments making up the society. For this purpose, it is necessary to use a “sequential formal representation” (scalars-vectors-matrices) across scales to generate a multi-dimensional (energy flows and production factors) representation of the metabolic pattern of the system.

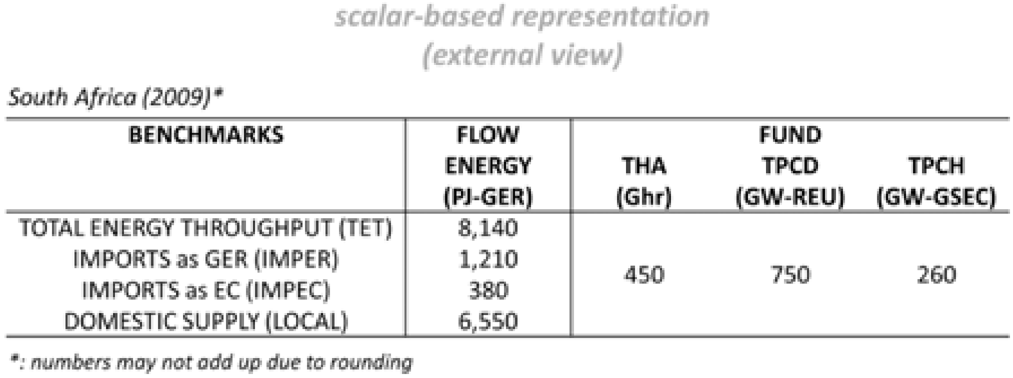
3.2.3 The sequential formal representation of energy flows

At this stage it is important to further explain the logic of the ‘sequential formal representation’ followed in this new protocol to energy accounting that is one of its fundamental features. In fact, when dealing with the energy flows of human societies it is easy to generate too much information that are not necessarily relevant for the assessment, and that eventually lead to overwhelm the analyst and blur the assessment – the typical dilemma encountered by those dealing with complex systems! To address this problem, the protocol therefore suggests the use of a ‘sequential formal representation’ of energy flows across scales which makes it possible to generate the necessary and sufficient information in relation to the typology of assessment at stake, whereas keeping information (and their corresponding inference!) available and accessible for assessments at other scales. As a matter of fact, each typology of quantitative assessment of energy flows presented in the previous section translates into a specific formal representation. That is, to each perception of energy flows corresponds a formal representation that is best suited for the specific use of this quantitative assessment. As this concept of ‘sequential formal representation’ of energy flows across scales is easier understood when using actual numbers, we provide an illustrative example of application for each one of those representations used in the protocol.

(1) Scalar-based representation of energy flows

The assessment referring to the perception from outside the society is formalized by means of *scalars*. As explained in the previous section, the Gross Energy Requirements (GER) are expressed in Joules of thermal equivalent. However, this assessment of Joules of GER does not refer to any actual flow of energy going through the society. Rather it corresponds to a generic conventional assessment (resulting from a choice made by the analyst!) used to compare in a standardized way different levels of energy consumption (both in quantity and quality) associated with human activity when comparing different countries. That is, this generic definition of "energy" referring to the perception from the outside is useful – and sufficient – for comparing the energy consumption of different countries. Indeed, this assessment must ignore the specific characteristics of the metabolic pattern perceived from the inside so that the comparison becomes possible in practice, manageable and communicable.

The scalar-based representation of energy flows is used in the multi-level/multi-dimension matrix which makes it possible to link an assessment of energy flows to other possible dimensions of analysis (e.g. food, water, monetary). An example of a multi-scale integrated characterization of the metabolic pattern of South Africa – used in the quantitative analysis of the case study developed in Chap. 5 – is illustrated in fig. 3.2. What is shown in this figure is the part of the dataset referring to the view from outside (see fig. 3.4). This can be detected by the fact that the various element of the multi-level matrix are scalars.



scalar-based representation
(external view)

South Africa (2009)*

BENCHMARKS	FLOW ENERGY (PJ-GER)	FUND THA (Ghr)	FUND TPCD (GW-REU)	FUND TPCH (GW-GSEC)
TOTAL ENERGY THROUGHPUT (TET)	8,140	450	750	260
IMPORTS as GER (IMPER)	1,210			
IMPORTS as EC (IMPEC)	380			
DOMESTIC SUPPLY (LOCAL)	6,550			

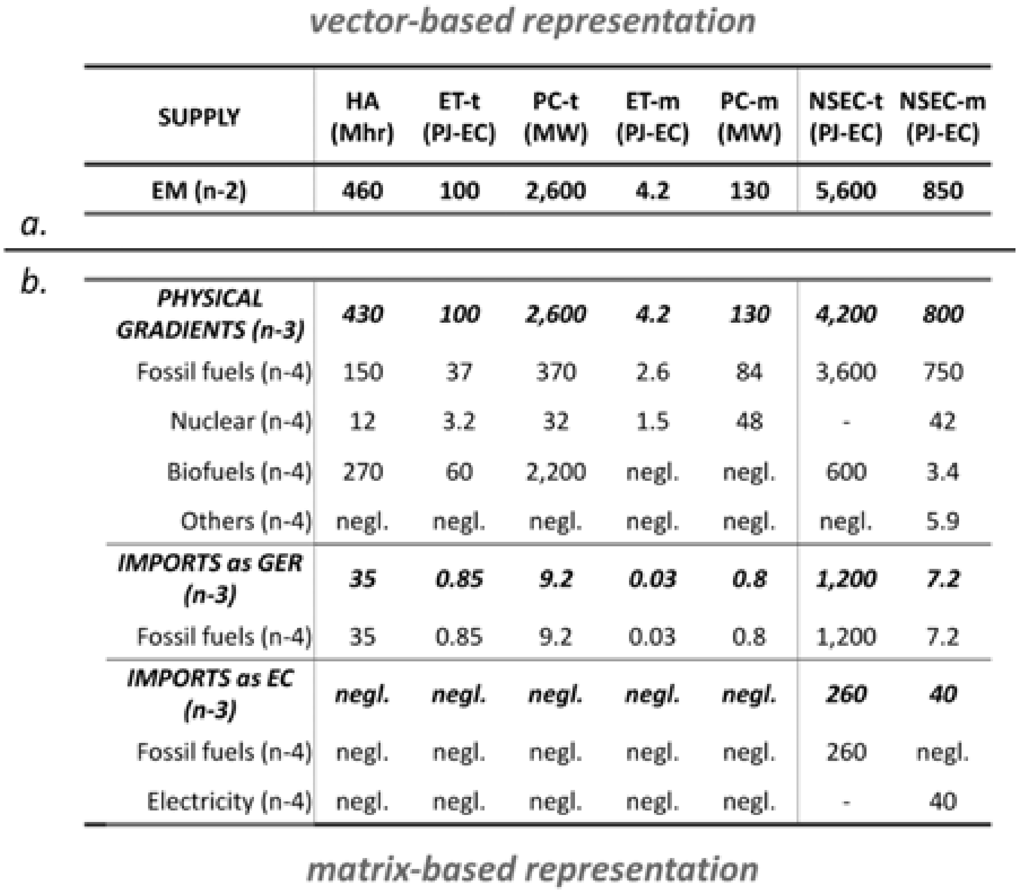
*: numbers may not add up due to rounding

Figure 3.2 The multi-level matrix characterizing the metabolic pattern of South Africa (4 flows, 3 funds – 5 compartments consumption; 2 compartments supply). EXTERNAL VIEW – assessments based on individual scalars.

(2) Vector-based representation of energy flows

The assessment referring to the perception from inside the society is formalized by means of *vectors*. These vectors characterize the different levels of energy consumption (both in quantity and quality) associated with different functions inside human societies. In the peculiar assessment describing the pattern of consumption of energy carriers within the Energy and Mining sector, the vector provides information referring to: (i) consumption of production factors – e.g. energy carriers (ET_t and EC_m), power capacity (PC_t and PC_m), human activity (HA) – and (ii) production of energy carriers ($NSEC_t$ and $NSEC_m$) – see fig. 3.3a.

In fact, what is illustrated in this figure is the part of the dataset referring to the inside view. In this vector-based representation, Joules of Gross Energy Requirements are divided in joules of Energy Carriers in the form of thermal energy (heat and fuels) and mechanical energy (electricity). In addition, contrary to the scalar-based representation used in the assessment from outside the society, the assessment from inside the society requires further information not just on “energy” but also on the consumption of production factors associated with the generation of the net supply of energy carriers. In addition, at this scale, it is important to keep separated the information referring to different energy carriers (thermal and mechanical) in the formal representation – hence the use of a vector in place of a scalar – as both the generation and consumption of different energy carriers entail different biophysical characteristics. The vector-based representation of “end uses” (including energy



vector-based representation

a.

SUPPLY	HA (Mhr)	ET-t (PJ-EC)	PC-t (MW)	ET-m (PJ-EC)	PC-m (MW)	NSEC-t (PJ-EC)	NSEC-m (PJ-EC)
EM (n-2)	**460**	**100**	**2,600**	**4.2**	**130**	**5,600**	**850**

b.

PHYSICAL GRADIENTS (n-3)	***430***	***100***	***2,600***	***4.2***	***130***	***4,200***	***800***
Fossil fuels (n-4)	150	37	370	2.6	84	3,600	750
Nuclear (n-4)	12	3.2	32	1.5	48	-	42
Biofuels (n-4)	270	60	2,200	negl.	negl.	600	3.4
Others (n-4)	negl.	negl.	negl.	negl.	negl.	negl.	5.9
IMPORTS as GER (n-3)	***35***	***0.85***	***9.2***	***0.03***	***0.8***	***1,200***	***7.2***
Fossil fuels (n-4)	35	0.85	9.2	0.03	0.8	1,200	7.2
IMPORTS as EC (n-3)	***negl.***	***negl.***	***negl.***	***negl.***	***negl.***	***260***	***40***
Fossil fuels (n-4)	negl.	negl.	negl.	negl.	negl.	260	negl.
Electricity (n-4)	negl.	negl.	negl.	negl.	negl.	-	40

matrix-based representation

Figure 3.3 Focusing on the energy supply of South Africa (5 production factors, 2 supply of energy carriers) INTERNAL VIEW – assessments based on vectors and matrices.

Fig. 3.3a shows the benchmarks of consumption of production factors and the production of energy carriers by the Energy and Mining (EM) sector (level n-2), considered as a sub-part of the Paid Work (PW) sector (level n-1) which is part from the Whole Society (level n). Fig 3b opens the vector of the EM sector into an energy supply matrix of the different primary energy sources and imports (levels n-3/n-4) making up the energy supply sector.

flows) is shown in the right part of the energy grammar which refers to the view from inside (see fig. 3.4).

(3) Matrix-based representation of energy flows

When looking inside the energy supply sector, it is necessary to open up the energy supply vector into a matrix showing the local primary energy sources and imports that compose this sector. In this way, the vector-based representation of the assessment at the level of the energy supply sector can be extended to a matrix-based representation as shown in fig. 3.3b.

(4) Wrapping-up the sequential formal representation of energy flows

To better explain the structure of relations associated with the different typologies of quantitative representation of energy flows we summarize in fig. 3.4 the sequential formal representation of energy flows across scales proposed in this protocol. The general multi-scale integrated characterization of a metabolic pattern is based on (i) a structure of a multi-level matrix made up of *scalars* (referring to the view from outside), that maps on (ii) a set of *vectors* (referring to the view from inside the society) that in turn are made of (iii) a set of multi-level *matrices* (referring to the view from inside a specific sector). The two main typologies of assessment (from the outside view and from the inside view) are linked together by using the energy grammar making possible to deal with non-equivalent energy forms across different scales. Fig. 3.4 illustrates an application of the multi-scale integrated assessment of the characterization of the metabolic pattern of South Africa when focusing on the ener-

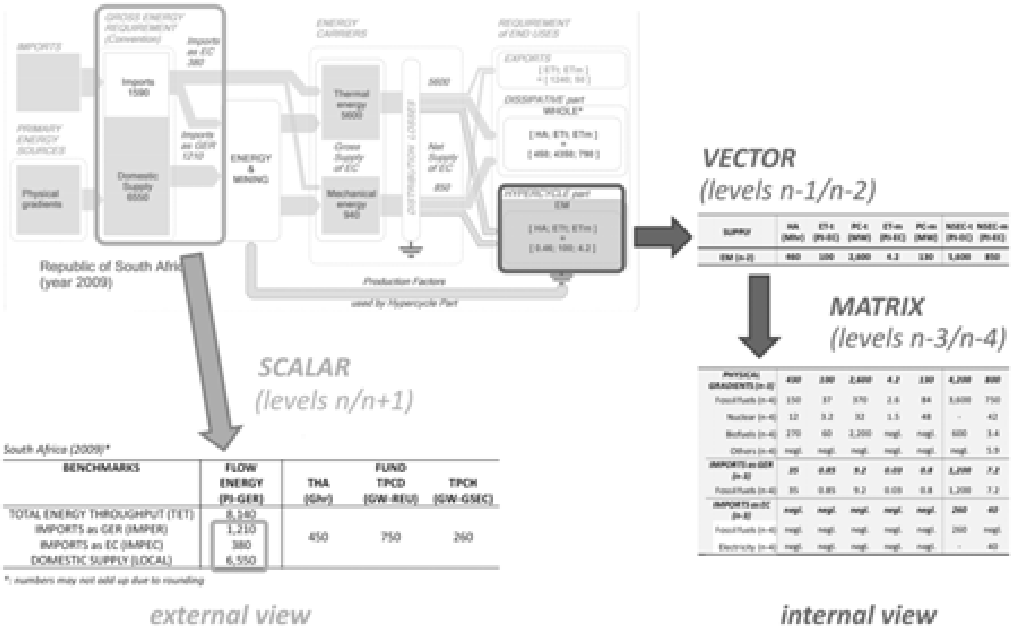


Figure 3.4 The sequential formal representation of energy flows across scales.

Notes: (1) the scalar-based representation refers to the assessment from outside the society (interface level n/n+1); (2) the vector-based representation refers to the assessment from inside the society (interface level n-1/n-2); whereas (3) the matrix-based representation refers to the assessment from inside the energy supply sector (interface level n-3/n-4).

gy supply sector.

3.2.4 How to generate numbers within the energy grammar

This section details how the different formalizations of energy flows shown in the energy grammar (Fig.3.1) are generated. First, it informs on the entry points that are the typologies of data used for all case studies. Then, it details the logical framework of the energy accounting system that is based on a set of steps presenting how the outputs are generated. The logical framework makes it possible to understand the formalization of the analysis, and especially how to deal with non-equivalent forms of energy in one integrated analysis. An example of application of this protocol is provided in Chap. 5 in the case of South Africa.

(1) Entry points

Three entry points are identified in the energy analysis, which correspond to the only data that can be measured (see fig. 3.5):

ENTRY POINT #1: Energy statistics on imports and local supply (at the level of the Primary Energy Sources)
Amount of fossil energy products either from imports or from domestic supply – expressed in biophysical units (i.e. tonnes, m3, etc.) or in thermal equivalent units (e.g. toe).

ENTRY POINT #2: Energy statistics on electricity generation and consumption (at the level of the End Uses)
Consumption of electricity per economic activities (agriculture, transport, construction, manufacturing, services, household, etc.) – expressed in Watt-hour (Wh).

ENTRY POINT #3: Technical coefficients of energy systems (at the level of the energy systems, for the most significant technologies)
Production factors required (consumption of energy carriers, human labor, land, etc.) and net supply of energy carrier (thermal or mechanical). The evaluation of the technical coefficients of each energy system requires using another grammar that makes it possible to assess the production factors required in the four standard unit operations (see Chap. 4).

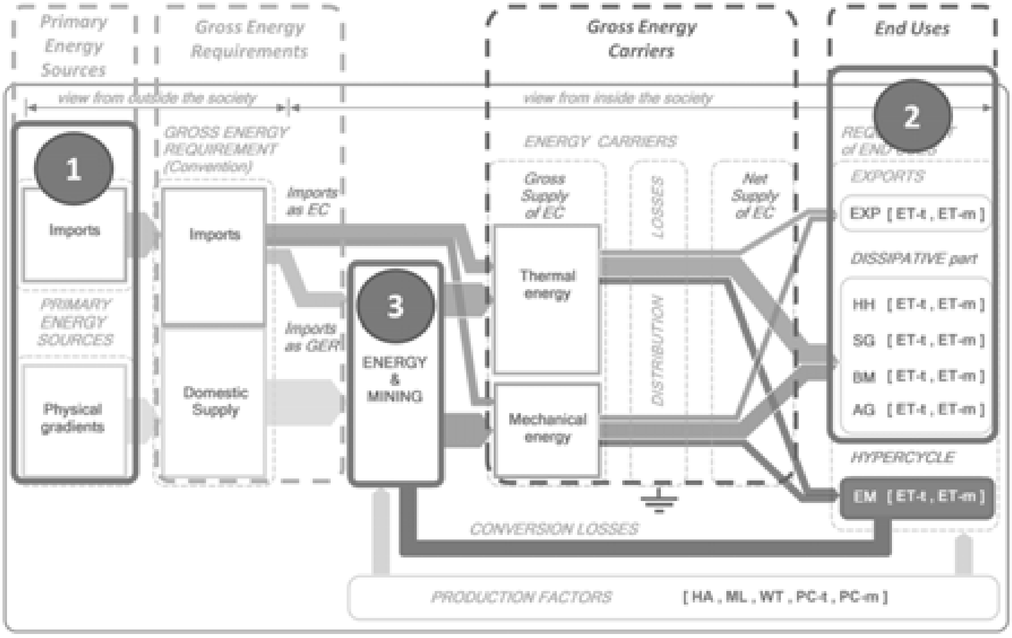


Figure 3.5 Entry points for the energy grammar.

Notes: (1) Energy statistics on imports and local supply; (2) Energy statistics on electricity generation and consumption; and (3) Technical coefficients of energy systems (require another grammar, see Chap. 4).

Beside these entry points, the formalization of the other energy forms (Gross Energy Requirements and Gross Supply of Energy Carriers) results from conventions made in the steps of the protocol. That is, those energy forms do not exist “per se” but rather are derived from the assessment of the characteristics of the energy supply sector.

(2) Logical framework

The logical framework used to generate the diagnostic analysis of the energetic metabolism of a system consists in a succession of steps dealing with different forms of energy – as illustrated in fig. 3.6.

Below, each one of the steps making up the logical framework is detailed:

STEP #1: PES/Imports category split – Step 1 consists in distinguishing the three categories of energy products: (1) imports as GER (IMPER), that are used for generating electricity; (2) imports as EC (IMPEC), that are directly consumed in the different sectors of society (End Uses); and (3) Primary Energy Sources that are coming from local supply. In addition, exports of EC are identified so as to equilibrate the energy balances. In this step, we only use data on energy statistics on imports and local supply.

STEP #2: GER (convention) and EC-split – Step 2 consists in evaluating the Gross Energy Requirement (GER) of each energy products as well as on obtaining the distribution between the different EC generated. For this purpose, we must track what the different energy products (PES and Imports) are used to generate (energy carriers as thermal or mechanical). In doing so, since we are dealing with non-equivalent forms of energy (GER and EC; and THERMAL and MECHANICAL), the formal evaluation of GER therefore results from a convention over the equivalence between GER/GSEC. Using data from Sorman (2011) we can assume:

- GER/GSEC-THERMAL = 1.00
- GER/GSEC-MECHANICAL = 2.60 (1/0.385)

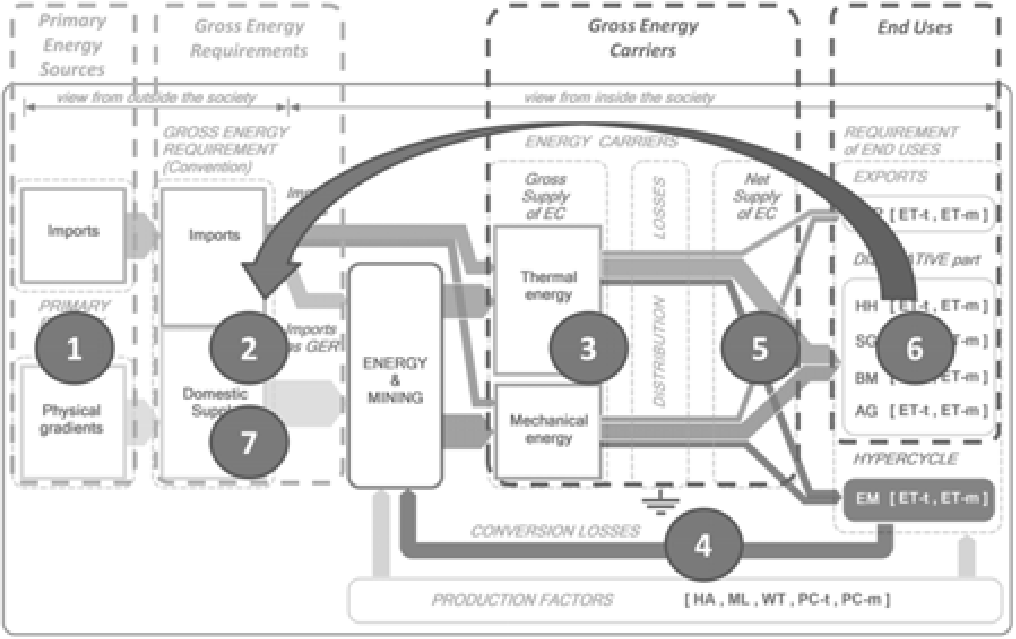


Figure 3.6 Logical framework used in the formalization of the energy grammar.

Note: In strict terms, the GER/GSEC ratios can be evaluated only after the End Uses have been characterized, which in turn requires a GER/GSEC equivalent ratio (impredicativity of energy analysis). As a matter of fact, these ratios only are used in order to provide an adequate split of EC. Then, the final evaluation of GER will use the iterated GER/GSEC (after the EU are characterized) obtained in step 6.

For this step, we use for THERMAL energy, data on energy statistics on imports and local supply; and for MECHANICAL energy, data on energy statistics on electricity generation and consumption. At this point, it becomes possible to express the GER-convention values per each energy product following the PES/Imports split made in step 1.

STEP #3: GSEC and LOSSES – Step 3 consists in evaluating the Gross Supply of Energy Carriers (GSEC) as THERMAL and MECHANICAL, as well as the LOSSES of distribution (considered as negligible for THERMAL energy) for each energy product. That way, it will be possible to evaluate the Net Supply of Energy Carriers (NSEC) generated by each PES/Import category.

Step #4: Characterization of the HYPERCYCLE – Step 4 consists in the characterization of the internal investment of energy carriers (conversion losses, as thermal energy and mechanical energy) and other production factors (power capacity, human activity, land use, water throughput) in the Hypercyclic part (EM sector) of the system.

Note: The consumption of the power capacity hypercyclic (PCH) follows a specific accounting procedure detailed in sect. 3.2.4.

STEP #5: NSEC-EU bifurcation – Step 5 consists in characterizing the End Uses (EU) allocated to each PES/Imports category based on the evaluation of NSEC derived from steps 3 and 4. When focusing on energy supply issues, the EU can be characterized as the Dissipative part (all sectors considered except the EM sector) once both EC consumed by the Hypercycle (EM sector) and sent as Exports are evaluated (see chap. 5 in the case of South Africa).

STEP #6: Characterization of REUD (DISSIPATIVE) – Step 6 consists in the characterization of the Requirements of End Uses in the Dissipative compartments (REUD) of the system, which correspond to the consumption of energy carriers (thermal and mechanical) and of other production factors (e.g. power capacity, human activity, land use, water throughput).

Note: The consumption of the power capacity dissipative (PCD) follows a specific accounting procedure detailed in sect. 3.2.4.

STEP #7: GER (iterative) per PES/Imports categories – Step 7 consists in formal evaluation of the total Gross Energy Requirement (GER) of each PES/Imports categories. For this purpose, we use the GER/GSEC ratio that derives from the characterization of the End Uses, hence different from the one used in step 2 as it is country- and year-specific.

STEP #8: DIAGNOSTIC of the energetic metabolism (not shown in fig. 3.6) – Once the seven steps of the logical framework have been followed, it becomes possible to perform one further step corresponding to the formal characterization of the diagnostic of the energetic metabolism of the system, which consists in building the multi-level/multi-dimensional matrix as shown in fig. 3.2 (external view). This formalization makes it possible to summarize information about the energetic metabolism for the purpose of deliberating at the nexus level where other dimensions (money, food, water, land) must be considered, as well as for performing the feasibility check. Then, it maintains the possibility of “opening the box” by looking at the set of vectors of production factors behind each number.

(3) The specific accounting procedure of power capacity

The Power Capacity (or technical capital) is one of the production factors used in bioeconomics – along with human activity and managed land – and probably is the one that has been the least explored and understood so far. The general concept of Power Capacity refers to the installed capital able to convert a given quantity of exosomatic energy flow (an input of energy carriers) into a flow of applied power (useful energy) at a given time scale (expressed in Watt).

It is important to mention that Power Capacity – that refers to actual converters (structure) converting energy flows – should not be confused with the concept of power level (or metabolic rate) described in sect. 3.2.5 – that refers to an assessment of the pace of consumption of energy flows in relation with human activity. That is, although their formalization refer to commensurable quantities (same dimensions), Power Capacity (a fund element) and power level (a flow/fund ratio) remain two non-equivalent quantities – the former being an estimate of the size of a specific production factor (the fund element exosomatic device), the latter an indicator of the metabolic characteristics (a flow/fund ratio).

Keeping this distinction in mind at all times, Power Capacity refers to the exosomatic converters either: (1) on the energy consumption side (e.g. machineries, appliances) – converters that consume energy carriers to express specific functions ("end uses", e.g. service, good) on the various compartments of society; or (2) on the energy supply side (e.g. refineries, power plants) converters that consume gross energy requirements to generate energy carriers (e.g. heat, fuel, electricity) to be delivered to the society.

As a matter of fact, we can identify two non-equivalent semantic definitions – and corresponding formalizations – of Power Capacity whether the assessment refers to:

(1) the energy consumption side – Power Capacity Dissipative (PCD) can be assessed using:

(i) a converter-based evaluation method based on the information gathered about the installed capacity of converters consuming mechanical (e.g. dishwashers, air-conditioners, computers) or thermal energy (e.g. planes, boats, trains, cars): PCD, expressed in Watt of Requirement of End Uses (W-REU).

The converter-based method used for assessing PCD can be described by the following steps:

* STEP #1: Power capacity of the converter (FUND element):

$PC_{i,j} = \sum_k [n_{i,j,k} \times PC_{i,j,k}]$, in W-REU. eq. (3.4)

This step requires information on the number $n_{i,j,k}$ of converters of type k consuming a given energy carrier j (thermal and mechanical) used in every compartment i – a BOTTOM-UP assessment.

* STEP #2: Energy input (EI) required by every converter is obtained from its power capacity and utilization factor: $EI_{i,j} = PC_{i,j} \times UF_{i,j} \times 8760$, (in J-EC, for every energy carrier j consumed inside compartment i), where $UF_{i,j}$ corresponds to the average utiliza-

tion factor of converters of type k using energy carrier j inside compartment i that is the product of two other factors:

$UF_{i,j} = \sum_k [OL_{i,j,k} \times CL_{i,j,k}]/n_{i,j,k}$, eq. (3.5)

where:
$OL_{i,j,k}$ = Operating Load (fraction of hours of the year of actual use of the converters of type k), and
$CL_{i,j,k}$ = Capacity Load (fraction of maximum power capacity of the converters of type k used as yearly average).

This step requires information on consumption behavior (hours of use, km travelled, etc.) embedded in the evaluation of the utilization factor (UF) of converters.

* STEP #3: The corresponding $EI_{i,j}$ (BOTTOM-UP assessment) is checked against the known $ET_{i,j}$ (= Requirement of End Uses inside the DISSIPATIVE parts or the HYPERCYCLE, expressed in J-EC) obtained in the energy grammar for every energy carrier j at the level of every compartment i (TOP-DOWN assessment): % of $ET_{i,j}$ covered by $EI_{i,j}$. This step requires having performed the assessment of the energetic metabolism of the system (see sect. 3.2.4).

* STEP #4: Then, the total Power Capacity Dissipative of energy carrier j at the level of compartment i can be estimated proportionally:

$PCD_{i,j} = ET_{i,j} \times PC_{i,j} / EI_{i,j}$. eq. (3.6)

This is the preferred method of accounting for the Power Capacity Dissipative whenever information about the converters is available.

(ii) a flow-based evaluation method by looking at the Energy Throughput (consumption of energy carriers for the making and maintenance of energy flows only, hence disregarding the making and maintenance of funds) $ET_{i,j}$ of the compartment i (expressed in J-EC per year):

$PCD_{i,j} = [(ET_{i,j} \times \mu_{i,j}) /(3600 \times UF_{i,j} \times 8760)]$, expressed in W-REU, eq. (3.7)

where $\mu_{i,j}$ corresponds to the conversion efficiency (applied power / energy input) at the level of the compartment i and specific to every energy carrier j (thermal and mechanical). This formalization method can be used as a first approximation of $PCD_{i,j}$

in situations where the converter-based method cannot be used in practice, i.e. when detailed information about the installed capacity of converters consuming energy carriers is not available.

By using either one or the other method of accounting, it becomes possible to define a vector of Power Capacity Dissipative for every compartment i:

$PCD_{i,j} = [PCD_{i,t} , PCD_{i,m}]$, whose terms are expressed in W-REU. eq. (3.8)

Then, in order to express the assessment of the Power Capacity Dissipative using only one scalar, it is necessary to sum the two terms of $PCD_{i,j}$ for every compartment i:

$PCD_i = (PCD_{i,t} + PCD_{i,m})$, see also sect. 3.4.2. eq. (3.9)

However, in doing so, it must be remembered that the two terms of $PCD_{i,j}$ are referring to conversion of non-equivalent forms of energy carriers (thermal and mechanical), so that it is important to keep information about the two terms making up the vector $PCD_{i,j}$, even when expressing PCD_i using one number.

Finally, the Total Power Capacity Dissipative (TPCD) can be defined at the level of the whole society as:

$TPCD = \sum_i PCD_i$ (expressed in W-REU). eq. (3.10)

It should be mentioned that since the energy supply sector requires an investment of energy carriers (conversion losses), therefore this procedure also applies to the Energy and Mining compartment (EM) in addition to the evaluation of its Power Capacity Hypercyclic (see below). This comes from the fact that the structures required to generate energy carrier using a given energy source cannot be reduced to one single facility (e.g. power plant) but rather requires other facilities (for an extended discussion over the processes and facilities required by power-supply systems, see Chap. 4).

(2) the energy supply side – Power Capacity Hypercyclic (PCH) can be assessed using:

(i) a converter-based evaluation method based on the direct information gathered about the installed capacity of power plants: PCH, expressed in Watt of Gross Supply of Energy Carrier (W-GSEC).

Similarly to PCD, the converter-based method to assess PCH can be described by the following steps:

* STEP #1: Power capacity of the power plants (FUND element):

$PC_i = \sum_j[n_{i,j} \text{ x } PC_{i,j}]$, in W-GSEC. eq. (3.11)

This step requires information on the number $n_{i,j}$ of converters of type j generating a given energy carrier i (thermal or mechanical) – a BOTTOM-UP assessment.

* STEP #2: Energy output (EO) generated by every power plant is obtained from its power capacity and utilization factor: $EO_{i,j} = [(PC_{i,j} \text{ x } 3600) \text{ x } (UF_{i,j} \text{ x } 8760)]$, (in J-EC, for every power plant j generating an energy carrier i), where $UF_{i,j}$ corresponds to the average utilization factor of the converters of type j used for generating energy carrier i that is the product of:

$UF_{i,j} = OL_{i,j} \text{ x } CL_{i,j}$, eq. (3.12)

where:
$OL_{i,j}$ = Operating Load (average fraction of hours of the year of actual use of the converters of type j), and
$CL_{i,j}$ = Capacity Load (average fraction of maximum power capacity of the converters of type j used as yearly average).

This step requires information on consumption behavior (hours of use, km travelled, etc.).

* STEP #3: The corresponding $EO_i = \sum_j EO_{i,j}$ (BOTTOM-UP assessment) is checked against the known $GSEC_i$ (= Gross Supply of Energy Carriers, expressed in J-EC) obtained in the energy grammar for every energy carrier i (TOP-DOWN assessment): % of $GSEC_i$ covered by EO_i. This step requires having performed the assessment of the energetic metabolism of the system (see sect. 3.2.4).

* STEP #4: Then, the total Power Capacity Hypercyclic of energy carrier i can be estimated proportionally:

$PCH_i = GSEC_i \times PC_i / EO_i$. eq. (3.13)

The converter-based method is the preferred method of accounting for the Power Capacity Hypercyclic. It is typically used for evaluating the installed power capacity of power plants used for generating electricity. Indeed, the power capacity of a power plant refers to its ability to generate energy carriers at full capacity which is generally labeled as such (e.g. a 1 GWe nuclear power plant) – i.e. information about the converter is available. However, there are situations in which such information does not exist.

(ii) a flow-based evaluation method by looking at the Gross Supply of Energy Carriers generated by the energy supply system over one year (in J-EC per year):

$PCH_i = [GSEC_i / (3600 \times UF_i \times 8760)]$, expressed in W-GSEC. eq. (3.14)

This formalization method is used in situations for which the converter-based method cannot be used, i.e. when there is no converter (imports as EC) or when information on the generating capacity of converters generating thermal energy (heat and fuel) is not available.

By using either one or the other method of accounting, it becomes possible to define the vector of Power Capacity Hypercyclic:

$PCH_i = [PCH_t , PCH_m]$, whose terms are expressed in W-GSEC. eq. (3.15)

Then, in order to express the assessment of the Total Power Capacity Hypercyclic (TPCH) using only one scalar, it is necessary to sum the two terms of PCH_i:

$TPCH = (PCH_t + PCH_m)$, expressed in W-REU (see also sect. 3.4.2). eq. (3.16)

However, in doing so, it must be remembered that, like for $PCD_{i,j}$, the two terms of PCH_i are referring to conversion of non-equivalent forms of energy carriers (thermal and mechanical), so that it is important to keep information about the two terms making up the vector PCH_i.

The two assessments of Power Capacity (Dissipative and Hypercyclic) presented above suggest that the systemic study of the maintenance and reproduction of power capacity in human societies – hence requiring dealing with a longer time scale – should be given more attention (an attempt to this purpose is developed in sect. 3.4.2). Again, it should be kept in mind at all time that these two assessments are non-equivalent, hence they should never be mixed together as one refers to the converters required to dissipate energy carriers (PCD, expressed in W-REU), whereas the other refers to the converters required to generate energy carriers (PCH, expressed in W-GSEC).

3.2.5 The set of indicators characterizing the energetic metabolic pattern

Here I summarize the set of indicators that can be generated by the protocol to energy accounting for the diagnosis analysis. In fact, when using the MuSIASEM approach as a diagnostic tool applied to the energy supply issues, several indicators can be generated so to characterize the existing energetic metabolic pattern of the system by providing information on:

(1) Flows of energy (defined as the flow element – EXTENSIVE VARIABLES useful for the VIABILITY and FEASIBILITY checks):

(i) the total requirement: Total Energy Throughput (TET), expressed in Joules of thermal equivalent (J-GER);

(ii) the degree of self-sufficiency (internal supply): Local Supply (LOCAL), expressed in J-GER;

(iii) imports: imports as GER (IMPER) or imports as EC (IMPEC), expressed in J-GER;

(iv) the fraction for internal consumption (conversion losses):

$vEM = [ET_{EM,t} ; ET_{EM,m}]$, expressed in Joules of energy carriers (J-EC); eq. (3.17)

(v) the fraction for dissipative end uses:

$vREUD = [ET_{REUD,t} ; ET_{REUD,m}]$, expressed in J-EC; eq. (3.18)

(vi) the losses (transmission):

$vLOSSES = [ET_{LOSSES,t} ; ET_{LOSSES,m}]$, expressed in J-EC; eq. (3.19)

<u>(vii) exports</u>: vEXPORTS = [$ET_{EXPORTS,t}$, $ET_{EXPORTS,m}$], expressed in J-EC.

In addition, the GER-to-EC conversion factors (accounting for the conversion losses) can be evaluated at the societal level: GER/GSEC-THERMAL and GER/GSEC-MECHANICAL. By using these conversion factors it becomes possible to express the above mentioned indicators of energy flows either in GER or EC as needed, while keeping track of information on its original formalization. In strict terms, the conversion factors differ among energy sources, so that their evaluation must be specified for each one of them to account for their specific characteristics of conversion (internal consumption). When doing so, the assessment generates a matrix of GER/GSEC vectors – [GER/GSEC-t , GER/GSEC-m] – considering all significant energy sources included in the energy supply sector. The evaluation of the conversion factors requires iteration (see sect. 3.2.4).

(2) Flows of energy in relation to fund element (a series of flow/fund ratios – INTENSIVE VARIABLES useful for the DESIRABILITY check):

<u>(i) the exosomatic metabolic rates</u>:

$vEMR_i$ = [$ET_{i,t}/HA_{i,t}$, $ET_{i,m}/HA_{i,m}$], expressed in J-EC per hour of human activity (at level *i*). eq. (3.20)

The metabolic rate refers to the concept of 'power level' (see sect. 3.4.1). Note that it is often difficult to get information on the human activity allocated to the consumption of different energy carriers (joint-production problem) so that the metabolic rates may be expressed in relation to the total human activity in the sector *i*, HA_i;

<u>(ii) the exosomatic metabolic densities</u>:

$vEMD_i$ = [$ET_{i,t}/ML_{i,t}$, $ET_{i,m}/ML_{i,m}$], expressed in J-EC per hectare of managed land (at level *i*). eq. (3.21)

As for the metabolic rates, information on the managed land allocated to the consumption of different energy carriers may be difficult to obtain so that the exosomatic metabolic densities may be expressed in relation to the total managed land in the sector *i*, ML_i;

(iii) the exosomatic metabolic intensities:

$vEMI_i = [\ ET_{i,t}/PCD_{i,t}\ ,\ ET_{i,m}/PCD_{i,m}\ ]$, expressed in J-EC per Watt of installed technical capital (at level *i*). eq. (3.22)

Contrary to the metabolic rates and densities, the power capacity allocated to each type of energy carrier is known in the metabolic intensity as it corresponds to the converters able to transform (consumption side) the specific energy carrier (e.g., a conventional car consumes fuels, a hair-dryer consumes electricity, but no jumbo jet consumes electricity . . .). The evaluation of power capacity requires information on the utilization factor (UF) of the converter that is the factor of the operating load (OL) by the capacity load (CL) – see sect. 3.2.4.

Those metabolic benchmarks can be evaluated at different scales (levels *i*), including the whole society and each one of the lower-level compartments defined in the accounting scheme, such as the various economic sectors. These ratios are then compared against reference values (benchmarks) describing ‘typical’ socio-economic systems (“typologies of countries”).

3.3 Simulation analysis: Checking the viability, feasibility and desirability of energy systems

The energy protocol presented in this chapter also provides insights on how to assess the viability, feasibility and desirability of energy systems.

3.3.1 Viability check

The viability of an energy system refers to its *quality* in relation to the characteristics of the energetic metabolic pattern from the supply side. This check is based on the check over internal constraints. The assessment of the *quality* of an energy system is checked in relation to the metabolic pattern of the whole society. (The comparison of the performance of different energy systems between each other is further detailed in Chap. 4). This can be performed by adopting an alternative formalization of the well-known concept of EROI that makes it possible to keep information on non-equivalent forms of energy carriers.

(1) The vectorial formalization of EROI

The concept of Energy Return on the (Energy) Investment (EROI) has been suggested in the field of energy analysis as an indicator of the "quality" of energy sources and more in general as a diagnostic tool to assess the performance of energy systems (Hall et al., 1981; Murphy and Hall, 2010). The basic rationale behind this concept is that an energy source shows a good quality if its return – an amount of energy carriers – is much larger than the quantity of energy carriers it requires for its operation. In spite of the clarity of this basic rationale in semantic terms, the formalization of the concept of EROI has always remained problematic (for a review, see Giampietro et al., 2012). However, the adoption of the MuSIASEM method of accounting makes it possible to avoid many of the epistemological troubles experienced by those trying to implement this concept using simple numbers. In fact, when adopting this grammar based on vectors and matrices it becomes easier to implement the concept of EROI. To explain how to apply the concept of EROI within this method of accounting, let's for a moment, imagine that the system is operating without imports or exports. The HYPERCYCLIC compartment (the Energy and Mining sector) uses a fraction of the available energy carriers (NSEC) for its own operation (vEM). With this investment of Energy Carriers (taking advantage of the favorable gradients provided by accessible Primary Energy Sources) the EM sector can generate a Gross Supply of Energy Carriers (vGSEC). Then the dynamic budget of energy carriers can be described starting from the compulsory energy investment (vNSEC-vREUD) that must be invested in the Energy and Mining sector (vET_{EM}) in order to obtain the required vGSEC (corresponding to the conversion losses). Therefore we can imagine that vGSEC represents the energy return to society generated by the investment of energy – vET_{EM} – made in the Energy and Mining sector. Put in another way, using this grammar we can get a new way of implementing the concept of EROI – Energy Return On the (Energy) Investment of an energy source *i* – using a characterization of energy flows based on the ratio between two vectors (representing flows of energy carriers as a mix of mechanical and thermal Joules) and also as a ratio between two matrices (describing set of vectors of "end uses"):

$$vEROI_i = vGSEC_i / vET_i = vGSEC_i / (vNSEC_i - vREUD_i) \qquad \text{eq. (3.23)}$$

This redundancy in the definition of EROI seems to go against the Occam's Razor, but in reality these two formalizations are not equivalent. The formalization based on a ratio between matrices makes it possible to characterize the society using dendrograms (profile of investment of fund and flow elements across compartments). That is, it makes it possible to establish a link between the characteristics of the society and a series of local characteristics of metabolic processes taking place simultaneously, at different scales – i.e. the characteristics of the local processes taking places in the four compartments to which the vectors of “end uses” refer to (a set of external referents observable only at different scales). The importance of this point and the concept of dendrograms are illustrated in Chap. 1.

(2) The $vEROI_i$ *<-> SEH check*

By adopting this alternative formulation of the concept of EROI, it becomes possible to compare alternative energy sources between each other when used in the same context (country and year). In addition, the vectorial formalization of the EROI can be used to check the *viability* of an energy source in relation with the metabolic pattern at the level of the society.

This is made possible by a check of the congruence between the vEROI of the system and the Strength of the Exosomatic Hypercycle (SEH) characterizing the energetic metabolism of the society. However, such assessment requires considering a vectorial definition of the concept of SEH in the same way it is proposed for the concept of EROI. In doing so, the definition of SEH becomes:

$$vSEH = WHOLE / HYPERCYCLE = vGSEC / vET_{EM} = vGSEC / (vNSEC - vREUD) \qquad \text{eq. (3.24)}$$

That is, the vectorial definition of the SEH is the same as EROI for individual energy systems with the difference that it is considered at the level of the whole energy supply sector. The SEH formalization hence represents the aggregated values of all energy systems making up the energy supply sector.

Note: An application of this alternative formalization of the concept of EROI is provided in Chap. 5 when assessing the viability of deploying nuclear power in South Africa.

3.3.2 Feasibility check

The feasibility of an energy system refers to its *size* required in relation to the existence of favorable boundary conditions and external gradients both on the supply side and the sink side. Assessing the feasibility of an energy system therefore consists in performing two sets of checks over external constraints:

(1) Checks on the supply side

(i) in relation to the requirements of local Primary Energy sources – Once the energy requirements of every energy source locally supplied have been evaluated (LOCAL, expressed in J-GER), and in the case information on Primary Energy Sources are available in biophysical units (e.g. tons of coal, hours of solar radiation, etc.), it becomes possible to map the requirements of energy flows onto the requirements of favorable gradients in the environment – GER/PES-equivalent, expressed in Joules of GER per unit of PES. As PES are specific to one specific favorable gradient – for which availability can be assessed locally (see below) – the assessment of the requirements of local PES consists in building a vector of GER_i/PES_i elements for each PES *i* making up the energy supply sector.

(ii) in relation to the existence of spatial constraints – The assessment of requirements of local PES must be completed by an assessment of availability of PES in relation to spatial constraints. As a matter of fact, such assessment must be performed locally using information based on GIS. The assessment of the availability of PES in relation to spatial constraints makes it possible to reveal potential nexus constraints (e.g. energy-food, energy-water) depending on characteristics of land uses in relation to human activity.

These two assessments referring to PES explain why characterizing the feasibility of an energy source – like it is the case of its viability and desirability – is country- and year-specific, so that in principles the feasibility cannot be deliberated in absolute terms.

(2) Checks on the sink side

(i) in relation to the availability of sink capacity from the environment – Using an Environmental Impact Matrix (using a selection of relevant indicators showing the integrity of the ecosystems potentially affected by the energy system). The selection of indicators characterizing the integrity of ecosystems is specific to each energy source, which are not necessarily equivalent between each other. For this reason, the assessment of the availability of sink capacity by means of the Environmental Impact Matrix requires – in the same way of the assessment of the availability of favorable gradients on the supply side – a check over local constraints both in space (e.g. requirement of land for dumping waste) and time (e.g. time of management required until the waste have been degraded/decayed). This assessment refers to the view from outside the society (compatibility with boundary conditions).

(ii) in relation to the availability of production factors (e.g. land, human activity, energy carriers) for handling waste/pollution generated by the energy system (a description of this standard unit operation of energy-supply systems is provided in chap. 4). This assessment completes the previous assessment by checking of sink capacity from inside the society (congruence among the parts) in relation to the availability of production factors required by a given energy system. However, in this case, this assessment based on the requirements of production factors makes it possible to compare the size of different energy source between each other (e.g. a nuclear power plant generating radioactive waste and a coal-fired power plant generating CO_2 emissions).

3.3.3 Desirability check

The desirability of an energy supply system refers to its *compatibility* with the characteristics of the metabolic pattern of society from the demand side – both at the level of the whole society and among the compartments.

In fact, after adopting a characterization based on a multilevel matrix of vectors describing the fund and flow elements in the different compartments (see sect. 3.2.3), it becomes possible to quantify the characteristics of the metabolic pattern of a society by dividing the quantities of the flows by the quantities of the fund elements. In this way, we can generate a series of flow-fund ratios – EMR, EMD, EMI, presented in sect. 3.2.5 – that make it possible to map energy flows with the funds under human control (land, power capacity and human activity).

This quantitative characterization based on three types of information – flows, funds and flow/fund ratios – describe the characteristics of the metabolic pattern of the selected funds and flows at the level of the whole society – how much funds, how much flows, what type of rate, density and intensity of these flows – are found in a society when looking at it at the level of the "black-box". When focusing on energy flows, we can use the dendrogram describing the profile of allocation of these overall quantities over lower level compartments to obtain a matrix of vectors describing these same three flow/fund ratios (intensive variables) across the chosen set of different compartments when looking at the parts operating inside the black-box (see fig. 1.4 of chap. 1).

These three typologies of flow-fund ratios refer to characteristics of the metabolic pattern (characteristics of the structural and functional compartments) that are observable only at the local scale and are extremely valuable to generate an integrated analysis across dimensions and scales – for an extended application of those flow-fund ratios to other dimensions of flows (food and water), see Giampietro et al. (eds.), in press.

By looking at the characteristics of the end use described by the vectors referring to specific compartments we can individuate the external referent of the quantitative assessment. For example, the vector describing the "end use" for energy supply in a developed society is *expected to* (since it belongs to a known typology): have less than 5% of the work force in the energy supply sector; use a lot of fossil energy both per hour and per hectare; and use a lot of power capacity per hectare. On the contrary, a poor country without high demographic pressure is *expected to* have a large fraction of the work force in agriculture, but a very low amount of power capacity (machinery) per ha in agriculture, and so on.

As we can see, the desirability of a given alternative energy source can therefore be assessed by looking at its *compatibility* with the set of expected characteristics (benchmarks) at the level of the energy supply sector and at the level of the whole society. It should be noted however that this check refers to the desirability defined in biophysical terms. That is, the desirability of an energy source can also be defined in socio-economic terms which requires considering values, beliefs, perceptions – a discussion about the socio-economic desirability of nuclear power is provided in chap. 2 and 6. It should be noted again that, given that the attributes of desirability are subject to change among individuals – especially after receiving relevant information about possible trade-offs – the deliberation over the desirability of an alternative energy source shall be conducted within a participatory process including relevant actors.

3.4 Beyond energetics: Dealing with different power levels across time scales

3.4.1 Non-equivalent perceptions of power level

As discussed in Chap. 1, the power level or metabolic rate corresponds to the ability of living systems to metabolize energy flows in time (for its formalization, see sect. 3.2.5 of this chapter). This indicator is essential for expressing their functions and reproducing themselves. Yet, energy flows can be perceived at different time scales entailing non-equivalent assessments:

(i) energy flows perceived over one day – This *micro*-scale is useful to characterize the local pattern of consumption of energy carriers among the different activities. It makes it possible to assess the performance of energy supply systems as regard to the characteristics on the demand side (although not sufficient for assessing the viability and desirability of alternative energy sources which requires considering the *meso*-scale). This time scale is also used when assessing the performance of energy converters on the dissipative part (e.g. microwave, electric car).

(ii) energy flows perceived over one year – This *meso*-scale is useful to characterize the average metabolic pattern of annual consumption of energy carriers among the different compartments of society, as well as the annual requirements of gross energy requirements on the supply side. This *meso*-scale is the one typically used by the energy protocol detailed in sect. 3.2 (diagnosis analysis of the energetic metabolic pattern of society) and sect. 3.3 (simulation analysis of alternative energy sources). At this scale the identity of the converters (fund elements) is assumed to be unchanged while the energy flows are transformed (flow elements).

(iii) energy flows perceived over the lifetime of the converter (e.g. one year, one decade, one century) – This *macro*-scale (and even *meta*-scale in the certain situations of a very long lifetime of the converters relatively to the pace of consumption of energy flows, e.g. handling of radioactive waste in the nuclear energy system, see Chap. 2) is useful to assess the investment required to make and maintain the converters (funds elements) – for an example of the evaluation of the production factors required to reproduce the nuclear energy system and the fossil-fuel system used for generating electricity, see Chap. 4. This assessment performed at the *macro*-scale is very useful in the discussion over the energetic transition of human societies. Yet, we reach another epistemological problem as, at this time scale, the converters cannot be considered as *fund* elements anymore, but rather as *flow* elements (see sect. 3.4.2).

3.4.2 Toward the study of 'powernetics'

As detailed in the previous section, dealing with the energetic transition of human societies requires adopting a larger time scale. Indeed, human society, like all living systems, has survived by increasing its "capacity to degrade energy" (power), and not simply by dissipating energy flows. This distinction referring to Odum's maximum power principle is crucial for assessing the sustainability of human societies (see also Chap. 1). It also makes it possible to address the missing piece in quantitative integrated assessment of complex systems that is the ability to deal with multiple time scales.

To worsen the situation, the time horizon of such assessment would depend on the society under study, which is characterized by the identity of the converters used in its dissipative and hypercyclic parts. That is, comparing the energetic transitions of pre-industrial societies, industrial societies, and eventually post-industrial societies would require considering non-equivalent time scales, letting alone the fact that they do not co-exist at the same period of time.

Here I provide some fundamental principles for the formal study of the 'powernetics' of human societies – the missing piece in the quantitative integrated approaches to sustainability science –based on (i) the theoretical advances in the field of complex energetics (see chap. 1), (ii) as well as the application of the MuSIASEM approach to energy flows (see sect. 3.2 and 3.3 of this chapter). It must be noted however that proposing an actual operationalization of powernetics would require further theoretical developments – so as to integrate the larger time scale in the MuSIASEM approach – and, above all, further empirical testing – so as to check its robustness and usefulness – something that is not included in this thesis.

(1) Semantic definition of "power capacity" at the macro-scale of time

Energetics that was originally defined as a systemic study of transformations among different energy forms was rapidly generalized as "the science of energy" (see Chap. 1). On the other hand, powernetics seeks to stand as the systemic study of the "capacity of energy transformation among different compartments of society". As a matter of fact, *Power Capacity* (formalized in energy per unit of time, expressed in Watt) becomes the flow studied in the field of 'powernetics', like is *energy* in the field of energetics.

In powernetics, the flow studied is no longer energy but power capacity that refers to the capacity of dissipation of energy carriers (expressed in energy per unit of time, e.g. Watt). In doing so, we extend the time scale of analysis to match the lifetime of the energy converters by adopting the *macro*-scale described in sect. 3.4.1. As such, Power Capacity which was a fund element of 'energetics' (along with Human Activity and Managed Land) becomes the flow element of 'powernetics'. As a matter of fact, the HYPERCYCLIC part in powernetics guaranteeing the supply of the power capacity to the rest of the society (taken as the DISSIPATIVE part) corresponds to the Building and Manufacturing sector (BM) – whereas it is the EM sector in energetics.

At this stage we reach an epistemological problem over the definition and existence of fund elements in 'powernetics'. In fact, at the macro-scale of time the converters cannot be considered as *fund* elements anymore, but rather as *flow* elements. This poses the question of what the existence of fund elements – i.e. systems whose identity remains unchanged – at the time scale involved when dealing with the energetic transitions of societies. This problem is especially relevant when trying to deal with converters that can be perceived over a very long time scale (e.g. the "nuclear energy system", see Chap. 2). Indeed, is there anything that can be considered unchanged over a period of a century – let alone one hundred thousands of years . . .? Even institutions are changing their identity over the time scales involved in energy transitions. As a matter of fact, probably it is impossible to identify any external referent (source of observables) when considering very large time scales so that when dealing with the perception of evolutionary patterns one may reach the limits of using quantitative approaches to sustainability assessment.

(2) Formal representation of 'power capacity' at the macro-scale of time

In the study of powernetics, Power Capacity refers to the capacity of conversion of energy at large scale both in space (the WHOLE society) and time (energetic transition). For this reason, the formalization of Power Capacity in powernetics must refer to the assessment of energy flows at large scale, hence in relation to the outside view of the whole society. In fact, at this time scale the identity of the parts of the system may change so that an assessment in relation to the inside view may not be reliable given the shorter expiration date of the assumptions about the boundaries and properties of the subparts. Then, we can define:

(i) the Total Power Capacity Dissipative (TPCD, expressed in W-REU) that is defined at the level of the whole society by one scalar as (see also sect. 3.2.4):

$$TPCD = PCD_t + PCD_m; \qquad \text{eq. (3.25)}$$

and, in the same way:

(ii) the Total Power Capacity Hypercyclic (TPCH, expressed in W-GSEC) that is defined at the level of the whole society by one scalar as (see also sect. 3.2.4):

$TPCH = PCH_t + PCH_m.$ eq. (3.26)

These two assessments of Power Capacity used to study societal transitions at large time scale require using the flow-based evaluation method given that there is no enough information about the converters (see sect. 3.2.4).

When comparing the two assessments of Total Power Capacity Dissipative (TPCD) – from the energy consumption side – and Total Power Capacity Hypercycle (TPCH) – one makes the counter-intuitive observation that they are not equal (TPCD being much higher than TPCH, e.g. see Chap. 5). Indeed, this is contrary to what is observed with energy flows, where there is a quantitative closure of the energy grammar (GSEC must be equal to the sum of the energy throughput allocated to either the DISSIPATIVE part, the HYPERCYCLIC part, or the EXPORTS – energy flows cannot disappear from the accounting system!). However, in the case of Power Capacity there is no closure between TPCD and TPCH as they refer to two non-equivalent assessments (see sect. 3.2.4).

Remembering H.T. Odum's maximum power principle being the ultimate driver for the development and the survival of living systems (see Chap 1), it becomes clear that human society has developed in the same way an ecosystem does, that is by extending its capacity to dissipate energy by taking advantage of favorable boundary conditions (abundant fossil fuel resources) making possible to temporarily develop away from thermodynamic constraints. For this reason, pre-industrial societies which did not have access to abundant energy sources were certainly having a much lower TPCD per capita. To the extent that, in the hypothetical case of a fully sustainable (a zero-sum game which cannot exist in practice, hence a living system being surviving or dying), the two assessments of TPCD and TPCH would match, i.e. the capacity of energy dissipation would be driven by the capacity of energy generation and *vice versa*.

(3) Potential indicators in 'powernetics'

(i) in relation to the assessment of the VIABILITY of an energetic transition:

In the same way the Strength of Exosomatic Hypercycle (SEH) compares the contribution of the HYPERCYCLE to the WHOLE society in terms of energy flows in energetics, the Strength of Power Capacity Hypercyclic (SPCH) can be defined in 'powernetics' as:

$$SPCH = PCD/PCH. \qquad \text{eq. (3.27)}$$

This indicator makes it possible to characterize the ability of the societies to increase their capacity to dissipate energy by reducing as much as possible to investment inside the hypercyclic part.

(ii) in relation to the assessment of the DESIRABILITY of an energetic transition:

An assessment of the Power Capacity can be performed in relation to (1) the period of energetic transitions (powernetic metabolic rate – PMR, expressed in Watt per year); and (2) the land use changes (powernetic metabolic density – PMD, expressed in Watt per hectare of managed land). Given the ignorance over the existence of fund elements in the study of 'powernetics', these two assessments refer to a series of flow/flow ratios – in place of the fund/fund ratios expected in the study of energetics.

It should be mentioned that it is not clear benchmarks values of these flow/flow ratios would even be available so as to make possible the check of the desirability. In fact, the evaluation of those benchmarks would have to consider past energetic transition of societies having an expiration date not compatible with a simulation analysis. To worsen the situation, those benchmarks may change over time so that it is clear that it would be impossible to define what is desirable from a transition point of view.

Yet, we reach here a very interesting situation – far from being a theoretical dead-end. Although the metabolic ratios characterizing the powernetic metabolism of a society cannot be formalized in substantive terms, human societies – like other living systems – may demonstrate 'patterns of recorded information' (see Chap. 1) acting like attractors in guiding their process of self-organization and development. Revealing the existence of such 'patterns of recorded information' would be a very useful indicator to better know the energetic evolution of human societies over the past and eventually understand the constraints ahead.

3.5 Conclusion

The new protocol – as a set of procedures – proposed in this chapter provides an integrated approach to energy accounting able to deal with multiple dimensions across multiple scales. That is, the protocol makes it possible to check the quality of alternative energy sources in relation to the energetic metabolic pattern of human societies based on three sets of assessments (providing specific indicators): (1) a check of its *feasibility* in relation to external constraints; (2) a check of its *viability* in relation to internal constraints; and (3) a check of its *desirability* in relation to expected benchmarks. An application of this protocol is provided in Chap. 5, which assesses the quality of nuclear power in South Africa.

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Chapter 4

Assessing the performance of energy systems*

This chapter provides an innovative approach for the characterization and comparison of the performance of energy systems, that is a critical piece of the alternative procedures developed in Chap. 3. By using another grammar that focuses on the standard unit operations of energy systems, it provides an evaluation of the technical coefficients and production factors required by their flow and fund elements. In doing so, the chapter compares the performance of the nuclear energy system, as defined in Chap. 2, to the fossil-fueled system used for generating electricity. The observed low biophysical competitiveness of nuclear energy compared to fossil energy when used to make electricity may explain the difficulties faced by nuclear energy to gain interest from investors explored in Chap. 6.

4.1 Introduction

The complexity of energy systems comes from the obvious fact that energy transformations of interest are governed by autocatalytic loops: energy systems must use energy carriers to generate energy carriers (see Chap. 3). For this reason: (i) their characteristics are unavoidably affected by non-linear relations; and (ii) they are operating simultaneously across different levels of organization and scales. To proper represent these processes we have to consider simultaneously different scales (see also Chap. 1):

(1) a local scale at which energy carriers are used to generate useful power – e.g. when the electricity of a power plant is used to power technical devices or liquid fuels are used for running engines. Using this scale we can assess information such

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as the value of power levels per hour of labor or the total consumption of energy carriers per year;

(2) a meso scale referring to the power capacity used by a plant – e.g. what type of converters are needed to generate the power output (e.g. measured in watts), that have to be maintained and reproduced. Using this scale we can assess the energy embodied in the technology used by the energy system discounted over its life span when considering the life-cycle assessment (LCA) of the energy embodied in technical capital;

(3) at a larger scale, we can assess the overhead for society associated with the labor requirements of an energy system – e.g. the hours of human activity required for the control of energy transformations. Using this scale we can establish a bridge with the socio-economic dimension of the process;

(4) expanding further the scale of analysis we can assess the compatibility between the requirement of Primary Energy Sources needed to produce the energy carriers and their availability in nature (feasibility in relation to boundary conditions).

As explained in previous books (Giampietro et al., 2011; Giampietro et al., 2012), mathematical models trying to collapse different types of quantitative information referring to different external referents observable only at different scales into a single system of inference must necessarily rely on a lot of assumptions and simplifications that unavoidably translate into quite unreliable results. This is the reason why the approach proposed in this chapter does not offer a “mathematical protocol” for analysis and comparison of energy systems, but a semantically open 'grammar’.

As introduced in Chapter 1, a 'grammar' is a set of expected relations over semantic characteristics of analyzed energy systems – that can be formalized “a la carte” by tailoring the chosen protocols on specific questions and situations. So what is proposed here is not a mathematical protocol to be applied “by default” to any situation independently from the particular system considered and its context. Indeed, we believe that the use of mathematical formalisms without an informed discussion about the implications of pre-analytical choices (the semantics of an analysis) may reduce the quality of the analysis. The method proposed here especially intends to avoid to the temptation of over-reductionism – what is called “formalism non-sense” – often found in energy analysis (Giampietro et al., 2011; Giampietro et al., 2012). That is, the choice of “relevant criteria”, “benchmarks for indicators used for each criterion” and the “weighting factors” cannot be done once and for all in a given protocol. Each choice requires a special tailoring depending on the context within which the integrated assessment takes place. For this reason, it is not recommended to apply or suggest a “substantive” method for weighting the importance of different criteria (Giampietro et al., 2006). In fact, the quantitative results show that an informed discussion over sustainability and energy systems does not necessarily require mathematical formalisms: when dealing with complex systems it is more important “to do the right sums rather than to get the sum right” (Toulmin, 2003).

This explains the use of the concept of grammar proposed here in which the pre-analytical choices done by the analyst must remain clearly visible, especially when considering also the unavoidable existence of uncertainty on the integrated characterization. In this way, when the actual analytical step is carried out (after crunching numbers) the users of the quantitative result can track back the series of decisions leading to the final quantitative results. The idea of finding “optimal solutions” becomes a mission impossible once we accept the idea of multi-criteria analysis. In this framework, the analysts working in integrated assessment should not be the ones selecting the relevant criteria, the targets and benchmarks, as well as the weighting factors to be used in the analysis. Rather, the analysts working in integrated assessment should help their clients (social actors and stakeholders) to carry out an informed process of deliberation based on a set of criteria, indicators, targets and weighting factors suggested or at least agreed by the users of the analysis.

4.2 The need of a double energy accounting

As recalled in Chapters 1 and 3, according to thermodynamic principles we cannot “make” energy. We can only exploit primary energy sources which represent favorable physical gradients outside human control. This exploitation requires investing production factors such as: (i) available energy carriers; (ii) power capacity; and (iii) labor. These production factors must be used as inputs in the process generating a net supply of energy carriers. This simple statement clearly indicates that if we want to characterize the performance of energy systems we have to use more than a single quantitative variable (Giampietro et al., 2012). That is, the quality of primary energy sources depends on several characteristics of the process adopted for their exploitation: (1) in relation to 'internal constraints' – we have to specify how much inputs – energy carriers, power capacity, human labor – we have to invest in a given set of energy transformations under human control to get a net supply of energy carriers

(Giampietro et al., 2012; Hall and Klitgaard, 2012; Smil, 2008; Giampietro and Mayumi, 2009; Hall et al., 1986; Murphy and Hall, 2010);

(2) in relation to 'external constraints' – we have to specify what is the overall size of favorable physical gradients outside human control – the amount of primary energy sources – which must be available on the supply side (biophysical constraint) and how much sink capacity is required from the environment to absorb the waste or pollution generated by the process (environmental impact).

These different pieces of information can only be obtained by considering an integrated set of quantitative variables referring to different semantic categories of accounting. In spite of the plausibility of this statement, when looking at the literature in energy analysis one can find that the quantitative analysis of the relationship between energy quality and economic performance is in general carried out using a variable at the time – e.g. individual ratios such as energy output per economic input (e.g. the price of energy carriers). In biophysical analysis, early works in this direction date from the 1980s and include attempts to use indices based on assessments of energy output per energy input (e.g. the index called EROI: Energy Return On the Investment) or thermodynamic concepts such as exergy analysis (Cleveland et al., 1984; 2000; Hall et al., 1986; Gever et al., 1991; Kaufmann, 1992; Hall, 2000; Ayres et al., 2003; and Ayres and Warr, 2005 – an overview in Giampietro et al., 2012). In general terms we can say that the use of mono-dimensional and mono-scale methods entails serious problems when the goal of the analysis is to deal with the issue of "energy quality". As explained more in details by Giampietro and co-workers (2012; Giampietro and Sorman, 2012) these methods cannot overcome the unavoidable ambiguity of the definition of the label "energy". That is, quantities of energy belonging to the category of Primary Energy Sources (e.g. tonnes of oil equivalent) are not "the same" as quantities of energy belonging to the category of Energy Carriers (e.g. kWh of electricity). Moreover, within the same semantic category – e.g. Energy Carriers – joules of a given energy form (mechanical energy or electricity) are not equivalent to joules of a different energy form (thermal energy).

The problem of equivalence between different energy forms calls back to the systemic ambiguity associated with the concept of energy, which can be trade to the origin of the science of "energetics" (Giampietro et al., 2012). In relation to this ambiguity we can say that, the science of thermodynamics has been especially developed for dealing with the consequences of the fact that different energy forms even if measured in the same quantity of Joules do have different qualities. The focus of the pioneers of thermodynamics, however, was mainly restricted to the problem of how to convert thermal energy into mechanical energy and vice-versa. By introducing the concept of thermodynamic cycles they found a way to characterize, in an analytical way, a given set of energy transformations – e.g. the Rankine cycle. That is, classic thermodynamics posed the problem of the existence of non-reducible differences in quality of different energy forms: e.g. 1 J of mechanical energy is not the same as 1 J of thermal energy. Then the work of Carnot, Joules and others made it possible to solve this problem by generating "equivalence criteria" within well-defined thermodynamic cycles (a conversion factor between Joules of thermal energy required to generate Joules of mechanical energy). Yet this solution based on the pre-analytical definition of a given set of thermodynamic cycles is not particularly useful for the analysis of the energetics of self-organizing systems, such as modern societies dealing with exosomatic energy (outside human bodies). Indeed, large complex systems operating across different scales can operate simultaneously using different technologies to carry out the same task (e.g. generating electricity using power plants operating with different efficiencies) and in different boundary conditions – e.g. the outside temperature for the processes going on inside the human body is stable and different from the temperature outside the human body. In such context, the use of equivalence criteria and quality factors (e.g. exergy) is limited (more information in Giampietro et al., 2012).

Moreover, as seen in Chapter 1, the innovative concepts introduced in the field of non-linear thermodynamics made things even more difficult to handle. When dealing with complex metabolic systems that act as dissipative systems whose identity has been frozen in time. According to the metaphor proposed by Schrödinger these systems define, on their own, what should be considered as a set of favorable gradients (negative entropy). That is, the definition of both what is an "energy input" and "waste" – to be adopted in a quantitative analysis – depends on the identity of the metabolic system. Gasoline is an energy input for a car, but not for a mule. Hay is an energy input for a mule but not for a car. In the same way, a jumbo jet cannot run onto electricity, in the case it were supplied with a "thermal equivalent" amount of joules. For this reason it is essential to account Joules of energy only after having established a set of relevant categories of accounting, since the simple indication of unspecified "quantities of Joules" is not sufficient to carry out a useful description of energy systems. Complex autopoietic systems (= systems generating themselves) require a pre-analytical tailoring of the categories used for their quantitative analysis on their specific characteristics and features. For this reason the quantitative analysis proposed in this chapter is not based on "quantities of energy" (i.e. a single number) but on vectors (i.e. an array of numbers) in which are specified using different categories: (i) the overall quantity of Joules of energy carriers; (ii) the fraction of thermal; and (iii) the fraction of mechanical energy (more details in Giampietro et al., 2012). This characterization can be used to check the compatibility of the supply of energy carriers with the characteristics of the requirement (end use). Using the metaphor of human metabolism, in order to develop knowledge about the physiology of a human being you have to observe first of all how the human body functions (what type of energy inputs are used to carry out which functions) and then to provide a more elaborated definition of the energetic intake (from carbohydrates, from proteins, from fats). The same applies to energy systems whose functions must be identified in order to discuss the energetic metabolism of society.

According to this rationale, when studying and comparing energy flows in different countries it is essential to perform (and keep separated!) two kinds of energy accountings (Giampietro and Sorman, 2012) referring to:

(1) Primary Energy Sources (PES) expressed in physical units such as tonnes of coal, kilograms of uranium) - the use of PES makes it possible to bridge the assessments made using energy variables with assessment made with non-energy physical units. This analysis is useful for dealing with environmental impact and biophysical constraints;

(2) Energy Carriers (EC) expressed in energy units such as joules or watt-hours – the use of EC makes it possible to bridge the assessments made using energy variables with variables useful for socio-economic analysis (i.e. prices and technical coefficients). This makes it possible to develop a new method of bio-economic analysis (proposed here) defining "bio-economic costs" in terms of requirements of production factors (hours of paid work, power capacity, and inputs of energy carriers) per unit of net supply. This analysis is useful for dealing with the existence of internal constraints defining the viability of a given energy system.

The innovative approach called MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) makes it possible the integrated handling of physical units, energy variables and other socio-economic variables (Giampietro et al., 2011; Giampietro et al., 2012, see also Chap. 3). Therefore, this approach makes it possible to differentiate the quantitative representation of “external constraints” – the biophysical constraints “and” environmental impact associated with the overall requirement of PES and generation of waste and pollution – from the quantitative representation of “internal constraints” – the viability of the proposed control over inputs of EC “and” of other production factors (Giampietro et al., 2011; Giampietro et al., 2012). In more general terms the MuSIASEM approach has been developed to provide an integrated assessment structured on a multi-criteria analysis capable of dealing with the complexity of energy systems as well as the inherent ambiguity associated with the concept of “energy” (Giampietro and Sorman, 2012).

4.3 The concept of grammar applied to the analysis of energy systems

4.3.1 The concept of grammar

In order to overcome the epistemological problems discussed in sect. 4.2 “quantities of energy” considered as relevant for the assessment can only be measured and aggregated after having agreed on a pre-analytical definition of a 'grammar' which has to be tailored on a given and finite set of energy transformations. A grammar consists in a set of expected relations linking 'semantic categories' (the different energy forms used in the process) and 'formal categories' (their relative quantification) according to a given set of production rules (the technical coefficients determining “transformities” among different energy flows). For a more detailed description see Giampietro et al., 2011, Chap. 6 and Giampietro et al., 2012, Chap. 9 and 10. An illustration of this concept applied to the case of power-supply systems is given in fig. 4.1.

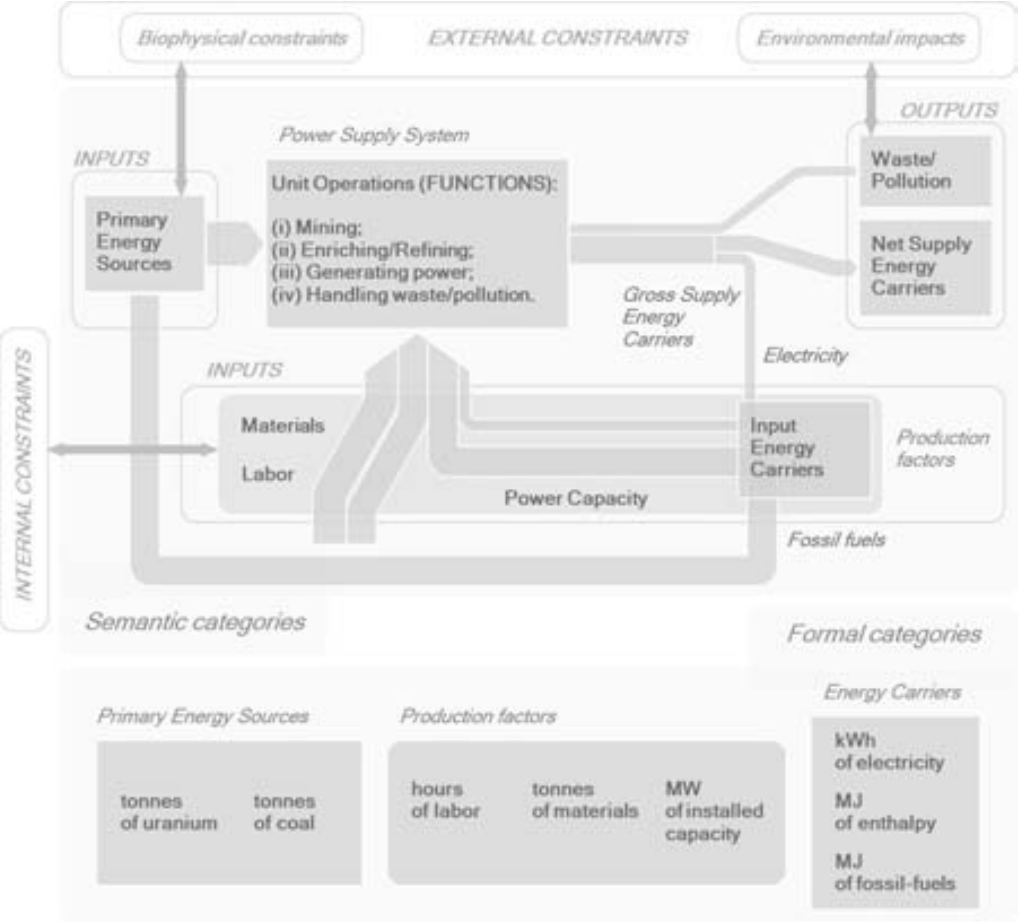


Figure 4.1 Semantic and formal categories for characterizing the performance of a power-supply system.

After having defined a Power-Supply System as an integrated set of 'unit operations' (functions, corresponding to the production rules of the system) capable of generating a net supply of electricity (output) from a given amount of Primary Energy Sources (input), we can make a distinction between the different semantic and formal categories needed to analyze and characterize the chosen set of energy transformations. Primary Energy Sources (a semantic category of energy form requiring the existence of favorable gradients whose existence is outside human control) can be quantified, using formal categories (proxy variable to which we can assign a value using a measurement scheme). For example, we can use kilograms of uranium (when assessing nuclear power plants) or tonnes of coal (when assessing coal-fired power plants) to assess the required quantity of Primary Energy Sources (PES) over a period of one year. The output and the inputs of "energy" associated with the process of exploitation have to be measured using another semantic category for energy accounting: Energy Carriers under human control (EC). In turn, these inputs and output have to be measured using different formal categories. Depending on the nature of the energy carrier considered we have to use different variables – e.g. kWh of electricity and MJ of enthalpy (or process heat) – when the quantitative accounting of these energy carriers refers to non-equivalent energy forms (e.g. thermal vs mechanical). Because of its ability to establish an agreed relation between the chosen semantics (perception of the issue) and the chosen formalization (representation of the issue) the pre-analytical definition of a grammar is essential. In fact, the grammar makes it possible to obtain a shared meaning about the numbers developed within the quantification process by identifying clearly the external referents – i.e. what is observed and what is described by the numbers. This is illustrated in fig. 4.1 in the case of power-supply systems where inputs and outputs are identified in semantic terms and put in relation to their external referents (internal and external constraints).

In summary, a grammar requires a pre-analytical agreement among those that will use the quantitative results about the "relevance" of the semantic categories and the "pertinence" of the formal categories and the production rules used in the protocol. When characterizing the performance of a power-supply system, exploiting primary energy sources to generate a net supply of energy carriers (output), this agreement has to refer to the series of choices required to establish a relation between: (i) the requirements of biophysical gradients outside human control (Primary Energy Sources, as inputs) – an information relevant for the analysis of biophysical constraints (external constraints); (ii) the requirements of sink capacity from the environment to absorb the waste and pollution generated (e.g. radioactive waste, carbon dioxide emissions, as outputs) – an information relevant for assessing the environmental impact (external constraint); and (iii) the requirements of production factors (inputs of power capacity, energy carriers, human labor) – an information relevant for an analysis of internal constraints. In the resulting integrated characterization these requirements must be calculated per unit of net supply of energy carriers, when considering the whole set of energy transformations taking place across the different energy forms involved in the process.

4.3.2 Defining a frame for assessing the performance of power-supply systems

The first step of the analysis is to identify the process of production of a net supply of a unit of Energy Carrier (e.g. 1 kWh of electricity) starting from a given typology of Primary Energy Sources (e.g. nuclear, coal, hydro). This production requires a series of different unit operations (or functions). By specifying these unit operations, first in functional terms and then by assigning to each function an associated structural type capable of expressing such a function, we can finally describe "what the power-supply system is" – using the MuSIASEM jargon we define the 'fund-elements' (Giampietro et al., 2012) – and "what the power-supply system does" – using the MuSIASEM jargon we define the 'flow-elements' (Giampietro et al., 2012) – across different levels of organization (parts/whole). Put in another way, we can generate such a representation only after having agreed on the need for a set of typologies of functions (why you need the various elements of the power-supply system) and the definition of typologies of structural organization (how the various elements of the power plant and the overall system work and express their function within or outside it). Therefore, in order to be able to compare the performance of different processes of production of energy carriers – in this example, power-supply systems producing electricity – it is important to individuate and define in the pre-analytical phase the set of tasks and relative compartments in charge for these unit operations determining the emergent property of "the power-supply system" that are common to the different typologies of power-supply systems.

That is, the grammar requires also a protocol of accounting capable of quantifying the chosen semantic categories. For example, favorable gradients can be measured in "potential heat" that can be extracted by available uranium minerals or in "potential heat" that can be extracted by available coal. Quantitative assessments of PES should be expressed in non-energy physical units (e.g. tonnes). In the same way, power capacity can be the capability of processing energy carriers in the process of exploitation of nuclear energy or fossil energy during the production of electricity (i.e. the physical converters needed to generate the power output measured in watts). The grammar therefore has to provide a protocol of accounting capable of establishing a relation between:

(i) the requirements of PES and of sink capacity – a quantitative definition of required inputs and outputs measured in non-energy physical units, that are relevant to assess the severity of external constraints;

(ii) the net supply of EC – a quantitative definition of flow output relevant to assess the performance of the power plant; and

(iii) the requirements of production factors – a quantitative definition of the inputs required to stabilize the output, an information relevant to assess the severity of internal constraints (the biophysical viability of the process).

4.3.3 Standard grammar of energy transformations within power-supply systems

Fig. 4.2 provides four examples of grammars characterizing the set of energy conversions taking place within different power-supply systems. In particular, by looking at the different energy conversions ("what the power-supply system does"), the standard grammar of energy transformations helps guiding on what energy forms (semantic categories and subsequent formal categories) must be included within the main label "Energy Carriers" in order to compare two different power-supply systems that use PES (of different forms) to generate a Net Supply of EC (electricity).

For instance, in the case of nuclear energy used for the production of electricity, the following set of energy transformations (or conversions) can be identified (PES = Primary Energy Source; EC = Energy Carrier):

- Conversion #1: PES to EC_{HEAT} (EC_{HEAT} = Process Heat or Enthalpy)
- Conversion #2a: EC_{HEAT} to EC_{MECA} (EC_{MECA} = Mechanical Energy)
- Conversion #2b: EC_{MECA} to gross EC_{ELEC} (EC_{ELEC} = Electric Energy)
- Conversion #3: gross EC_{ELEC} to net EC_{ELEC} (final output of Net Supply of EC)

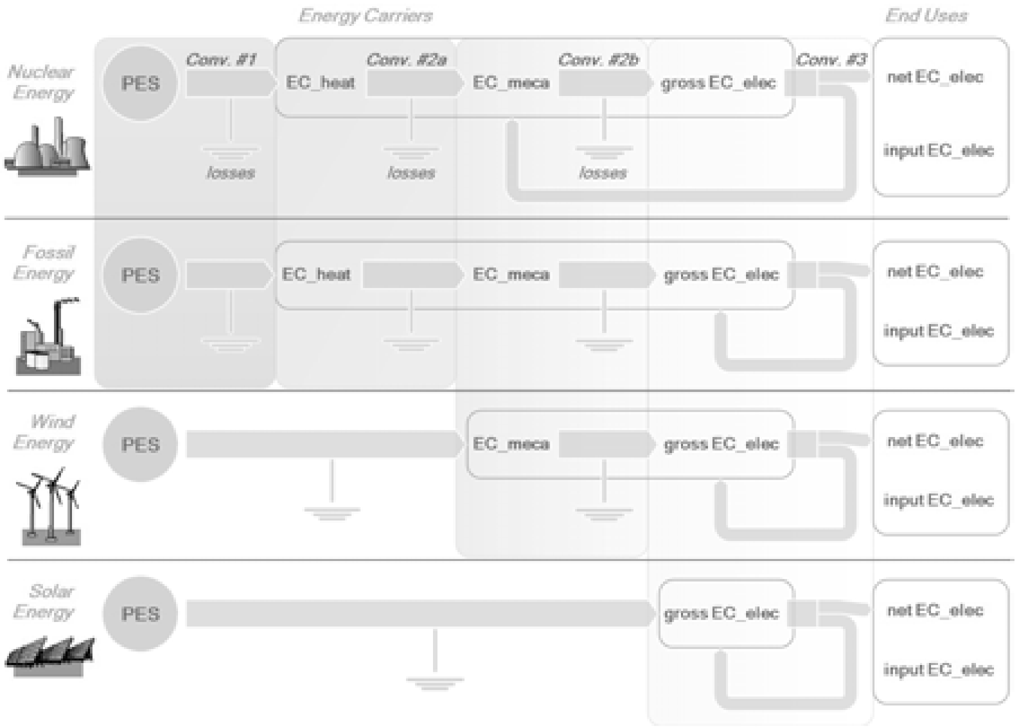


Figure 4.2 Standard grammar of energy transformations for power-supply systems.

A comparison based on our grammar clearly indicates that nuclear energy and fossil energy present a striking similarity in the overall structure of energy transformations. Indeed, nuclear energy and fossil energy present the same set of energy transformations when producing electricity. In addition, within those two systems, Process Heat and Mechanical Energy are introduced as EC although they are not directly delivered to society (End Uses). Also, Conversion #3 does not strictly correspond to an energy transformation but rather to a loss of EC due to the “energy for energy” dissipative part (something common to all power-supply systems).

As a matter of fact, it becomes possible to compare the performance of nuclear energy and fossil energy for making electricity (the “whole”) by looking at the characteristics of each one of their sub-processes (the “parts”). In doing so, we can use the following four standard functions describing the unit operations of both systems: (1) Mining; (2) Refining/Enriching; (3) Generating power; and (4) Handling waste / Controlling pollution.

4.4 Case study – Comparison between power-supply systems based on nuclear energy and fossil energy

4.4.1 The comparison scheme of the process of electricity generation

This study adopts a biophysical representation of the metabolism of socioeconomic systems based on Georgescu-Roegen's (1971) flow-fund theoretical scheme. In this scheme, 'flows' (e.g. energy inputs, material flows) refer to elements disappearing and/or appearing over the duration of the representation (time horizon of the analysis), while 'funds' (e.g. capital/power capacity, workers/hours of labor) refer to agents that are responsible for energy transformations and are able to preserve their identity over the duration of the representation (for a more detailed description see Giampietro et al., 2011, Chap. 7).

Fig. 4.3 presents an application of the flow-fund scheme used to compare the various 'processes' (transformation of energy flows) and 'facilities' (making and maintenance of the funds) within each one of the four unit operations for the production of electricity with nuclear energy and fossil energy: (1) Mining; (2) Refining/Enriching; (3) Generating power; and (4) Handling waste / Controlling pollution. Each one of these unit operations is made of sub-processes that make it possible to perform the successive energy transformations presented in fig. 4.2. In particular, each energy conversion covers the following sub-processes:

- Conversion #1: sub-processes of the “Mining”, “Refining/Enriching” and “Generating power” (“Generating heat” only) unit operations;
- Conversion #2a: sub-processes of the “Generating power” (“Rankine cycle” only) unit operation;
- Conversion #2b: sub-processes of the “Generating power” (“Generating electricity” only) unit operation; and
- Conversion #3: internal consumption of electricity as losses during the “Generating power” (“Generating electricity” only) unit operation.

Note: the sub-processes of the “Handling waste / Controlling pollution” unit operation occur outside the energy conversions.

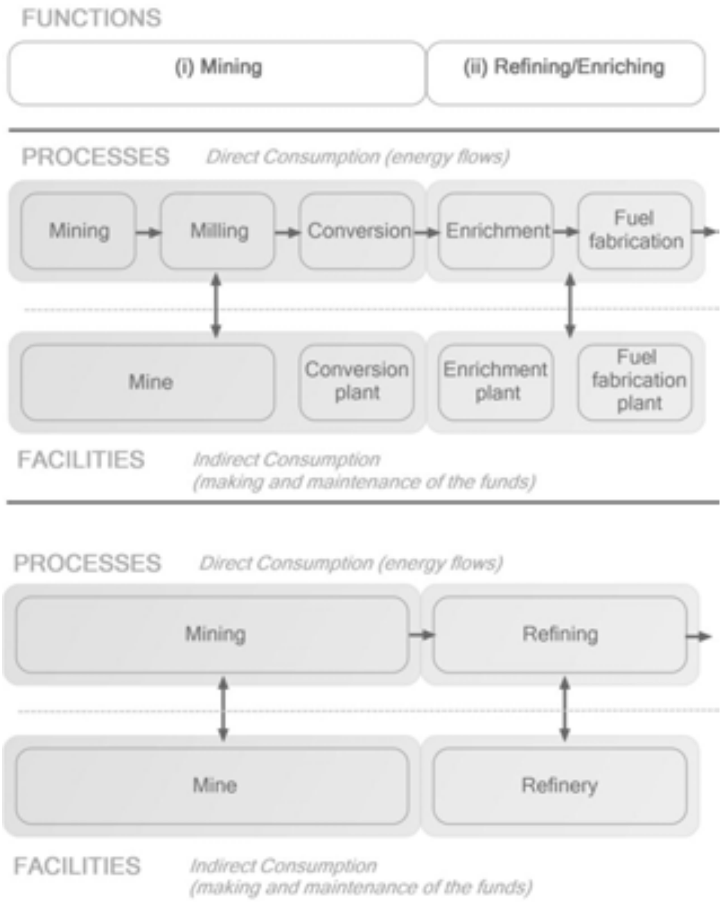
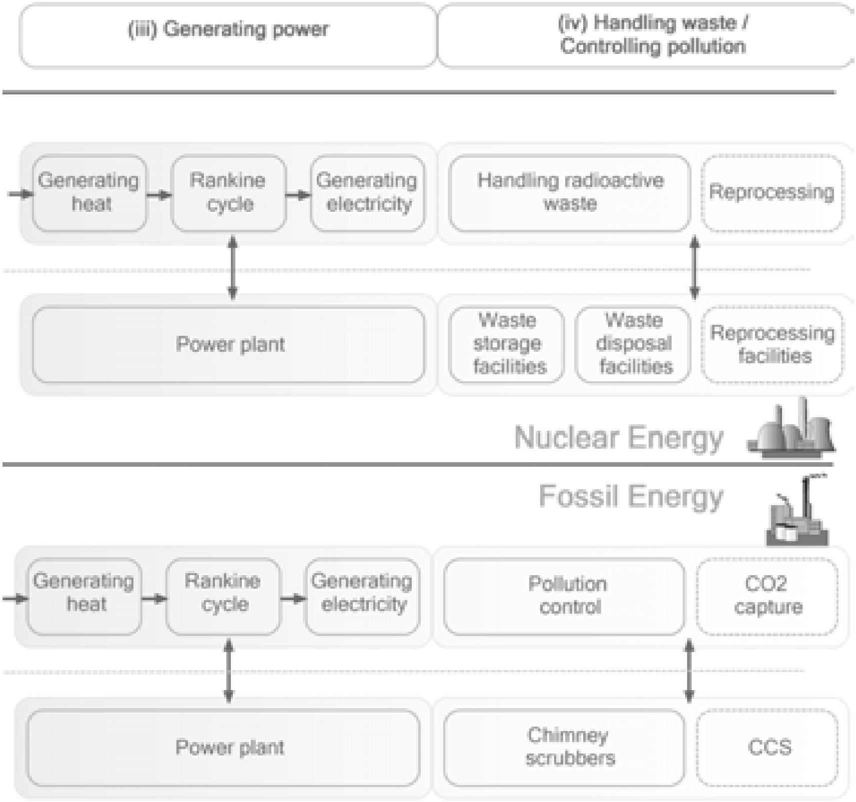


Figure 4.3 Comparison scheme of the process of electricity generation – Nuclear energy vs. Fossil energy.

The four unit operations for the production of electricity represent the main semantic categories (in relation to the production rules within the systems) used to carry out the quantitative assessment. In this way, it becomes possible to compare the performance of different power-supply systems considering the characteristics of each one of the sub-processes distributed among each unit operation.

From fig. 4.3, we see that the various processes of the "Generating power" unit operation are the same. However, since the facilities involved in this unit operation (power plants) are quite distinct between the two power-supply systems, this will translate into significant quantitative differences in the corresponding sub-processes (see the assessments reported in sect. 4.4.3). In relation to the other unit operations, the two systems present qualitative differences in the set of processes and fa-



cilities prior to generating Process Heat (Conversion #1 in fig. 4.2) – that is during the "Mining" and "Refining/Enriching" unit operations – and after generating electricity (Conversions #2b and 3 in fig. 4.2) – that is during the "Handling waste / Controlling pollution" unit operation.

The remainder of this section consists in (i) describing and characterizing the baseline cases of both power-supply systems (sect. 4.4.2); (ii) presenting the general scheme of the study (sect. 4.4.3); and (iii) evaluating the biophysical requirements of the two systems generating electricity when using this grammar (the calculations are given in Appendix I).

4.4.2 Description of the baseline cases used for the comparison

Two baseline cases are considered for each one of the two power-supply systems assessed leading to a total of four cases identified throughout the study as follows:

- Case 1: Nuclear energy – Light Water Reactor (LWR) power plant;
- Case 2: Nuclear energy – LWR power plant with reprocessing;
- Case 3: Fossil energy – Integrated Gasification Combined Cycle (IGCC) power plant;
- Case 4: Fossil energy – IGCC power plant with Carbon Capture and Storage (CCS).

The selection of those two couples of baseline cases for the comparison between advanced technologies of the fossil energy and nuclear energy systems for the production of electricity is mainly motivated by (1) the availability of the selected technology (Cases 1 and 3); and (2) the pace at which new designs can be deployed and become a representative technology in the worldwide electricity generation from either nuclear or fossil energy (Cases 2 and 4).

On that respect, advanced designs of fossil energy power plants including carbon dioxide (CO2) capture (Case 4) are considered as an available technology (or soon to be) whose deployment would be much faster than the future generation of nuclear power plants (generation IV), a technology not yet available, whose deployment would require many decades (if they are to be ever deployed) before becoming a significant technology within the nuclear energy system (see Chap. 2).

The same applies for “fission” versus “fusion”. Indeed, only nuclear “fission” energy is considered here as it corresponds to the only application currently performed from thermonuclear physics for industrial purposes (excluding medical applications) – mainly in the production of electricity[27]. Although, research about potential commercial application from nuclear “fusion” energy is achieving some progress as the experimental stage is expected to start in the mid-term – through the ITER project announced to be in operation by 2019 – followed by a demonstration stage – the

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[27] The use of nuclear fission energy for the production of industrial process heat is not within the scope of this study although it represents one possible application of the same technology based on nuclear energy.

future DEMO prototype power plant – announced to be operational by 2040 (ITER, 2012). Even assuming as accurate these time estimates, we cannot realistically expect nuclear fusion to become a significant (primary) energy source for supplying electricity (an energy carrier) over the 21st century.

Indeed, even the commercial application of nuclear fusion energy before the end of this century can be questioned as (i) there are still fundamental research questions that have not been answered yet by the community of nuclear fusion scientists – such as the experimental impossibility to reach a self-sufficient tritium breeding process necessary for fusion power plant operation (Dittmar, 2012); (ii) there is a systemic problem when scaling-up a new nuclear power program mainly due to the different degrees of complexity between academic-reactor operations and an operational-reactor fleet – which has been the case during the first nuclear fission energy era (Bupp and Derian, 1978; Yang, 2009; Grubler, 2010; see also Chap. 6); and (iii) the deployment of fusion nuclear power plants would imply a nuclear-fuel cycle transition which requires between 50 and 100 years to happen (Kazimi et al., 2011) which would be further delayed if a new fleet of Generation IV reactors is to be deployed in the meantime, or simply because of the existing technological lock-in that affects nuclear technology (Arthur, 1989; Cowan, 1990; see also Chap. 6). For those reasons, nuclear fission energy is very likely to remain the only nuclear energy source over the entire 21st century and maybe beyond into the future.

As far as the nuclear fuel cycle, according to a study from the Massachusetts Institute of Technology (MIT), the LWR partly-closed fuel cycle consisting in reprocessing the plutonium and uranium implies a reduction of the enriched uranium fuel demand of about 15% and 10% respectively (Kazimi et al., 2011). According to the same study, the spent used nuclear fuel (SNF) can only be reprocessed one or two times. The partly-closed fuel cycle is therefore currently used only as an experiment both in France and in the UK, and its potential large scale deployment would require between 50 and 100 years (Kazimi et al., 2011). In addition, since it also raises proliferation concerns it does not represent today a significant fuel cycle option. Nevertheless, it has been considered in this study (Case 2) in order to evaluate the effects of the reprocessing operations on the performance of the nuclear-based power-supply system, letting alone the other problems raised above.

It should be noted that the sizes of the two plants (nuclear and fossil) that are compared are different. However, this does not affect the validity of the comparison. In fact, the relative size of these two types of power plants (1300 MW for nuclear power plant and 480 MW for IGCC power plant) reflects the typical size of existing plants. In fact, it is well known that the most significant technologies for nuclear power and IGCC technology do show different power outputs in the range of the power output considered here. The power output of these two technologies is, in fact, determined by optimization factors determining their size, meaning that this "typical size" should be expected as associated with the technology. Clearly, moderate changes in the size around these typical values may affect the technical coefficients calculated here. In any case, the different orders of magnitude in the requirement of some production factors per unit of net supply of electricity between the two systems (see sect. 4.4.4) suggests that the issue of scale, unless of dramatic changes in the technology, can be neglected in this type of comparison.

Case 1: Nuclear energy (LWR power plant)

The case of the nuclear-based power-supply system considers the same baseline case of a typical 1300MWe power plant with a light water reactor (LWR) as used by Lenzen (2008) along with a once-through nuclear fuel cycle meaning that no reprocessing is being considered during the process of production, as shown in Fig. I.1 of Appendix I.

LWRs – including pressurized water reactors (PWR) and boiling water reactors (BWR) – represent about 90% of the worldwide installed capacity of nuclear power plants connected to the grid (CEA, 2010), while most new plants are on average 1300MWe – from 1000MWe to 1600MWe. The capacity load factor (CL) of 79% – shown in Tab. 4.1 – corresponds to the average power output over the period of availability of all currently operating LWRs in the World (CEA, 2010). This factor reflects the actual use of the converter, that is, its actual "net output of energy" (which corresponds to our "gross supply of electricity" before taking into account the input of electricity required by the overall power-supply system). The burn-up (or heating value) corresponds to the amount of thermal energy extracted from initial nuclear fuel in the reactor, expressed in gigawatt-days per metric ton of uranium (GWd/t). It depends on the nuclear fuel re-load of the reactor – 45GWd/t corresponding to the average value for LWRs (Lenzen, 2008). The uranium fuel (UO2) consumption of 25t/y comes from the mass balance evaluation detailed in (Diaz-Maurin, 2012). This is consistent with the average values of 20t/GWe per year (Kazimi et al., 2011) corresponding to about 26t/y for the selected baseline case. This corresponds to 181tU/y of natural uranium requirements[28], the main difference with the uranium fuel consumption coming from the depleted uranium (UF6) that exits the system after the enrichment process (see Fig. I.1 of Appendix I).

It shall be mentioned that the burn-up depends only on the technology used for the reactor, not on the uranium ore quality. Indeed, as mentioned before, the burn-up is imposed by the frequency at which uranium fuel is re-loaded into the reactor while uranium fuel is adapted to the reactor type. The quality of uranium ore (grade or natural enrichment) then plays a role in the enrichment process – the lower the uranium grade, the more enrichment effort required (Diaz-Maurin, 2012, sect. 4) – hence ultimately influencing the requirements of production factors (labor, materials, power capacity) of the overall system in order to process the same amount of natural uranium (Yellow Cake, U3O8) and then supply the same amount of uranium fuel (UO2) to the power plant (reactor).

Such a defined nuclear power plant generates about 100,000TJ of process heat (or enthalpy, in our case of an isobar process) corresponding to about 9,000GWh of (gross) electricity per year.

Table 4. 1 Parameters of Case 1.

Parameter	**Value**	**Unit**	**Source**
Burn-up	45	GWd_{th}/t_U	Lenzen, 2008
Uranium fuel consum.	25	t_U/y	see fig. I.1 of Appendix I
Process heat generated	97 600	TJ/y	
Plant capacity	1300	MW_{el}	Lenzen, 2008
Capacity Load	79%	(World av. for LWR)	After CEA, 2010
Electricity generated	9000	GWh_{el}/y (gross supply)	

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[28] Natural uranium requirements are expressed in terms of tons (t) of contained uranium (U) rather than in terms of uranium oxide (U3O8).

Rankine cycle efficiency (gross)	33%		

Case 2: Nuclear energy (LWR power plant with reprocessing)

Case 2 differs from Case 1 by including a reprocessing phase into the nuclear fuel cycle, as shown in fig. I.2 of Appendix I. The reprocessing operation consists in the partial recycling of the used fuel (uranium) and products of the fission reactions (plutonium), as well as in the reprocessing of the depleted uranium (UF6) which operations reduce the consumption of natural uranium down to 152tU/y for the same power plant. This process is further detailed by Diaz-Maurin (2012). Tab. 4.2 presents the parameters of the baseline Case 2 which are essentially the same as Case 1 since the reactor technology remains the same. The only difference is that the nuclear energy production process now is not only burning enriched natural uranium (corresponding to 16tU/y) but also reprocessed fuel – i.e. mixed oxide fuel (MOX, corresponding to 5tHM/y) and reprocessed uranium (UO2rep, corresponding to 4tU/y), see fig. I.2 of Appendix I – so that the annual heated material (HM) consumption remains equal to 25tHM/y as for Case 1.

Table 4.2 Parameters of Case 2.

Parameter	**Value**	**Unit**	**Source**
Burn-up	45	GWd_{th}/t_U	Lenzen, 2008
Heated material consum.	25	t_{HM}/y	see fig. I.2 of Appendix I
Process heat generated	97 500	TJ/y	
Plant capacity	1300	MW_{el}	Lenzen, 2008
Capacity Load	79%	(World av. for LWR)	After CEA, 2010
Electricity generated	9000	GWh_{el}/y (gross supply)	
Rankine cycle efficiency (gross)	33%		

Case 3: Fossil energy (IGCC power plant)

For the fossil-based power-supply system, a 480MWe Integrated Gasification Combined Cycle (IGCC) power plant using coal has been considered as the baseline case of this study. The coal-based IGCC technology, presented in fig. I.3 of Appendix I, corresponds to one of the new advanced designs of fossil-fueled power plants discussed in a study from the MIT (Katzer et al., 2007) and whose latest baseline designs have been assessed by the U.S. Department of Energy (US DOE/NETL, 2010). The IGCC technology consists in turning the coal into gas in order to remove impurities before it is combusted, improving the overall efficiency of the power plant compared to conventional coal-fired power plants.

Contrary to nuclear energy, the heating value of a fossil-fueled power plant does not depend on the selected technology but rather on the type of coal being mined (e.g. bituminous, lignite, etc.) – from which derives its heating content. As a matter of facts, the heating value of 26GJ/t – shown in tab. 4.3 – has been calculated according to the proportion of each coal type being exploited in recoverable reserves (see Diaz-Maurin, 2012, Table 7). The capacity load factor (CL) is taken equal to 80% (US DOE/NETL, 2010, Section 2.5], where it is assumed that the capacity load factor is equal to the availability of the converter since “each new plant would be dispatched any time it is available and would be capable of generating maximum capacity when online” (more details on those factors are provided for the evaluation of the power capacity, sect. I.4 of Appendix I). This leads to a coal consumption equal to 1.45Mt/y (after US DOE/NETL, 2010). The Rankine cycle efficiency is considered equal to about 40% (after US DOE/NETL, 2010), which shows some improvements in the efficiency over the previous IGCC designs (38% in Katzer et al., 2007). On that respect, it shall be noted that the Rankine cycle efficiencies have been evaluated by removing the electricity requirements of the “Mining” and “Handling waste / Controlling pollution” unit operations for which electricity requirements will be accounted separately in Appendix I. The difference of efficiencies between Case 3 and 4 is therefore due to a lower performance of the same processes – i.e. the lower efficiency of Case 4 only translates the losses in the same equipments when the system contains a CCS technology and does not include the electricity requirements that go into the equipments of the CCS itself.

Such a defined fossil-fueled energy power plant generates about 37,100TJ of process heat and about 4,200GWh of (gross) electricity per year. The corresponding power plant capacity is then equal to 480MWe.

Table 4.3 Parameters of Case 3.

Parameter	Value	Unit	Source
Heating value	26	GJ/t_{coal}	Diaz-Maurin, 2012, Table 7
Coal consum.	1.45	Mt_{coal}/y (av.)	After US DOE/NETL, 2010
Process heat generated	37 100	TJ/y	
Rankine cycle efficiency	40.4%	(av.)	After US DOE/NETL, 2010
Electricity generated	4200	GWh_{el}/y (gross supply)	
Capacity Load	80%	(equal to the availability)	US DOE/NETL, 2010
Plant capacity	480	MW_{el}	

Case 4: Fossil energy (IGCC power plant with CCS) – 90% of CO2 capturing

Case 4 differs from Case 3 by adding a carbon capture and storage (CCS) technology which reduces the CO2 emissions of the power plant by 90%. The IGCC technology is one of the leading candidates for electricity production with CO2 capture (Katzer et al., 2007; US DOE/NETL, 2010; Rubin et al., 2007), which justifies our baseline case of IGCC+CCS. Although those new designs are still under development – especially the CCS technology included in this Case 4 – they are considered as the next generation of fossil-fueled power plants and are already being deployed in some places.

The CCS technology requires a certain amount of process heat – depending on the rate of CO2 being captured, being here 90% – mainly due to the gas-compression needed before injecting the carbon into the ground (see fig. I.3 of Appendix I) so that the Rankine cycle efficiency drops from 40% down to about 34% (after US DOE/NETL, 2010) as shown in tab. 4.4. In order to compensate part of the loss of efficiency, the coal consumption is increased to 1.52Mt/y (after US DOE/NETL, 2010) so as to generate the same amount of gross process heat. The (gross) process heat of such a defined fossil-fueled power plant is equal to about 39,100TJ per year which difference with Case 3 is due to the higher annual coal consumption. Then, the net process heat (36,500TJ/y) generated by the selected fossil-fueled energy power plant can directly be derived from the loss of Rankine cycle efficiency. The corresponding power plant capacity is then equal to 420MWe.

Table 4.4 Parameters of Case 4.

Parameter	**Value**	**Unit**	**Source**
Heating value	26	GJ/t_{coal}	Diaz-Maurin, 2012, Table 8
Coal consum.	1.52	Mt_{coal}/y (av.)	After US DOE/NETL, 2010
Process heat generated	39 100	TJ/y (gross)	
Rankine cycle efficiency	40.4%	(av. w/o CCS)	After US DOE/NETL, 2010
	33.7%	(av. w/ CCS)	After US DOE/NETL, 2010
Process heat generated	36 500	TJ/y (net)	
Electricity generated	3700	GWh_{el}/y (gross supply)	
Capacity Load	80%	(equal to the availability)	US DOE/NETL, 2010
Plant capacity	420	MW_{el}	

4.4.3 Description of the general scheme of the study

As shown in fig. 4.4, all inputs and outputs referring to the semantic categories are expressed in their own units referring to their corresponding formal categories as described in fig. 4.1. As discussed in sect. 4.2, we do not perform any aggregation based on fixed conversions referring to "quality indexes" for different energy forms (the approach of reductionism) reduced to a single measurement unit. This refers back to the joint-production dilemma that is one of the systemic methodological problems of conventional energy analysis (see Chap. 1).

There are two main categories of inputs that enter into the system: (1) the requirements of PES (uranium and coal) necessary to generate the supply of EC; and (2) the production factors necessary for the processes to operate properly and that include (i) electricity; (ii) power capacity (derived from the fossil-fuels requirements), (iii) labor; and (iv) other key materials. In addition, the outputs exiting the systems refer to (1) the Net Supply of EC (electricity) generated by the system, as well as (2) the waste and pollution generated during the process of production.

This integrated evaluation is carried out in two steps: (1) defining the Net Supply of electricity generated by the system (net GWh) using a given set of energy transformations (see fig. 4.2). This is an assessment based on intensive variables – e.g. requirement per unit of output; and (2) evaluating the inputs and outputs (unit per net GWh) relevant for the later analysis of external and internal constraints. This analysis uses both intensive variables – e.g. technical coefficients, when analyzing qualitative differences – and extensive variables – e.g. total requirements or total emissions – when scaling qualitative information. Indeed, as explained in sect. 4.3, in order to compare the two energy systems, all inputs must be expressed per unit of Net Supply of electricity obtained after evaluation of the electricity requirements (Input) and Gross Supply of electricity generated within each system. That way it becomes possible to compare power-supply systems (fossil energy and nuclear energy) independently from their specific power capacities.

In order to make possible such a comparison, all cases must address the implications of the internal requirements of electricity (Input) of the system (see fig. 4.4) in order to evaluate the Net Supply of electricity to which the biophysical requirements will be compared. This is of capital importance for the study because the whole process might differ in terms of requirement of input of electricity – and so in terms of net supply of electricity – also when the Rankine cycle efficiency of the power plants (producing the gross supply of electricity) are of the same order of magnitude. Again, although we provide the characteristics of each unit operation according to the grammar (sect. 4.3), the aim of the study is to characterize the performance of the "whole" (overall production process) after characterizing the performance of the "parts" (sub-processes distributed within the four unit operations).

After the integrated evaluation of the performance of the systems (inputs entering into the system, the technical factors necessary to operate the processes and the outputs exiting the systems), it becomes possible to perform the actual integrated assessment of the two systems in relation to different external referents. Such an

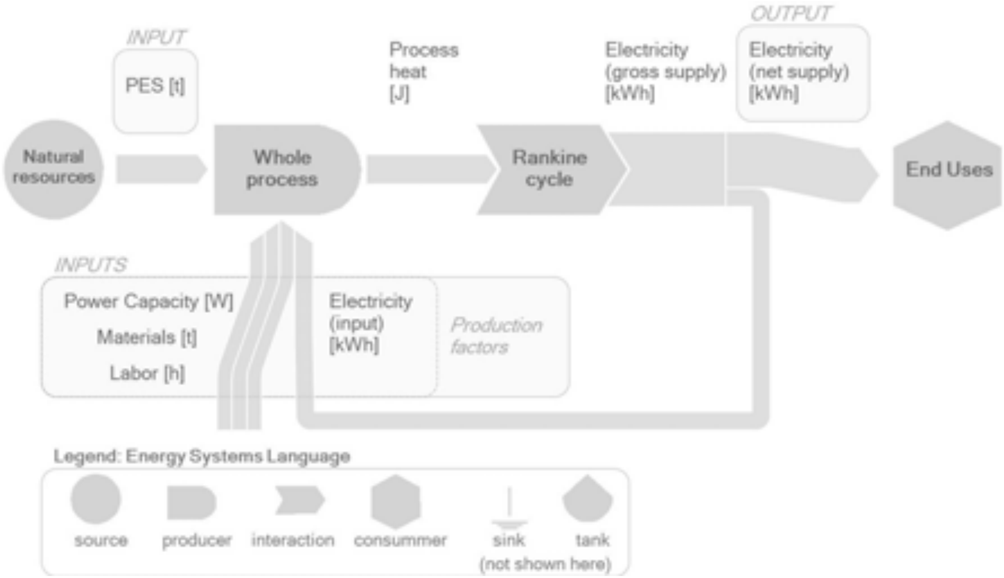


Figure 4.4 General scheme of the study (Cases 1 to 3).

integrated assessment provides a "contextualized" picture of the performance referring to the severity of external constraints and internal constraints as seen in fig. 4.1. For reasons of space, we will only provide an example of assessment of the PES requirements of the two systems in relation to the World coal and uranium reserves, the main objective being here to present our new approach of using grammars to assess the performance of power-supply systems.

Figures 4.4 and 4.5 use the energy systems language first proposed by H.T. Odum (1971) as a common denominator expressing all the flows and processes together in order to understand a whole system and the full interaction of the parts (Brown, 2004).

As shown in fig. 4.5, the general scheme of Case 4 differs from the other cases by considering an additional internal requirement of process heat (J) due to the CCS technology as explained in sect. 4.4.2.

In order to evaluate the different biophysical requirements for the four cases of the study, the annual material balance has been performed for each production process. Each material balance includes the different sub-processes related to the fuel in all its successive forms – from the mining of natural resources to the handling of waste or pollution. Results of the material balances are shown in fig. I.1 and I.2 of Appendix I

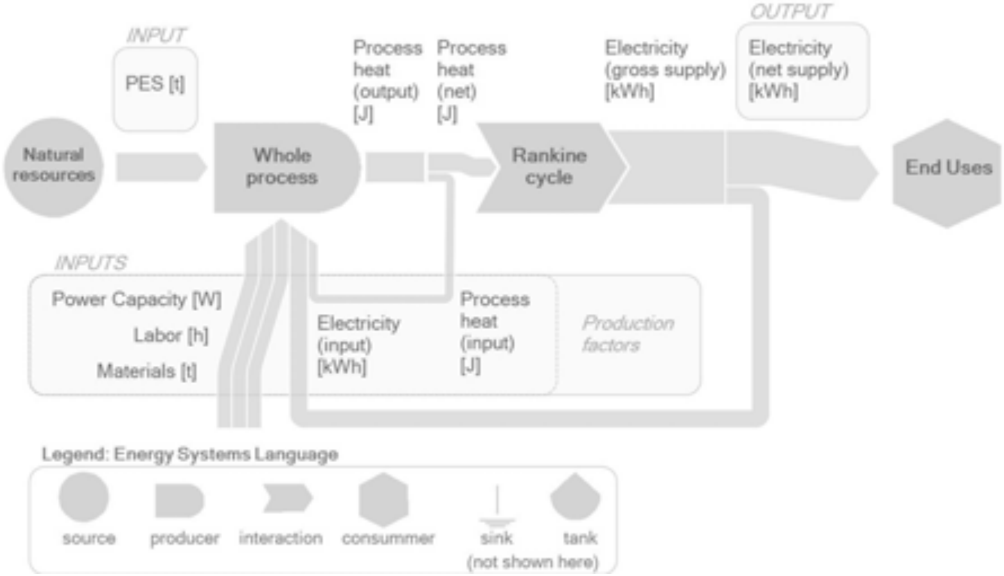


Figure 4.5 General scheme of the study (Case 4).

for nuclear energy, and in Tables 3 and 4 for the fossil energy. For more details on the calculations, see Diaz-Maurin, 2012.

4.4.4 Integrated characterization of the performance of the power-supply systems

The integrated characterization of the performance of the power-supply systems is performed in Appendix I which presents the evaluation of all inputs and outputs for the four baseline cases presented in sect. 4.4.2 following the general scheme presented in sect. 4.4.3.

4.4.5 Discussing the performance of nuclear energy and fossil energy

Fig. 4.6 summarizes the integrated evaluation comparing the performance of the nuclear- and fossil-based power-supply systems (considering two technical solutions for each PES) whose inputs, outputs and technical coefficients have been evaluated in Appendix I. The summary presented below adopts the semantic and formal categories presented in fig. 4.1.

(1) Characteristics relevant for the analysis of external constraints

(i) Biophysical constraints on the supply side: requirements of PES (inputs)

From fig. 4.6, we see that the requirements of PES is between 17 and 21 kilograms of uranium per net GWh of electricity for nuclear energy and between 350 and 470 tonnes of coal for fossil energy.

In relation to the analysis relevant for external constraints the overall requirements of PES (uranium and coal) must be compared to the overall availability of the natural resources (mineral form and fossil form, respectively) to provide meaningful information. That is, in order to be complete, the assessment of external constraints must be performed in relation to an external referent, namely the amount of PES available at the level of one country or a group of countries depending on the scale of analysis. Although this is not within the scope of this chapter that mainly focuses on the definition of a new methodology for assessing the performance of power-supply systems, this approach flags the crucial importance of two key factors that could potentially affect the functioning of those systems: the availability and the quality of PES. An example of the integrated assessment of PES in relation to external constraints is provided in sect. 4.4.6 (and fig. 4.7).

(ii) Environmental impact on the sink side: waste and pollution (outputs)

The other quantitative indicators relevant for the analysis of external constraints are the quantities of waste and pollution determining the sink capacity required from the environment. In the case of radioactive wastes they have to be handled for a long time period before they can be neutrally released to the environment. The duration of this period can reach the order of magnitude of 100,000 years in the case of the most radioactive wastes (HLW) – a very long time span that is very difficult to account for in energy analysis. Indeed, over such a time scale the “handling waste” operation becomes a fund element in relation to the time scale of the analysis of energy flows (generally fitting the lifetime of the power plant). Fund elements are constituent that preserve their identity during the analytical representation so that they participate to the definition of “what the system is”. As a matter of fact, this means that when discussing the performance of nuclear energy compared with other power-supply systems, we should consider the biophysical costs associated with additional fund element even though these costs cannot be assessed within the same time scale. This fund element will remain there thousands of years after the original power plant will be decommissioned!

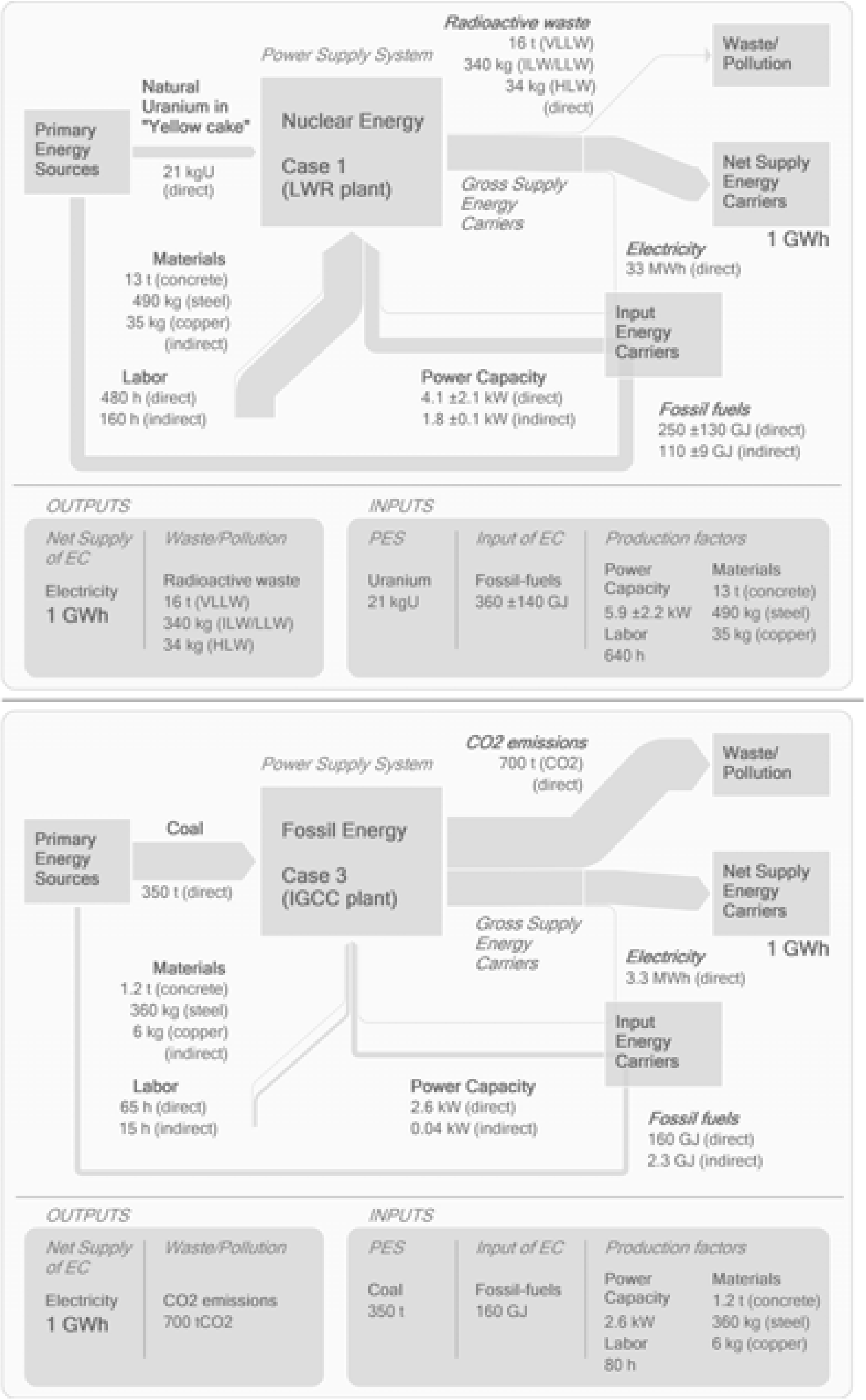
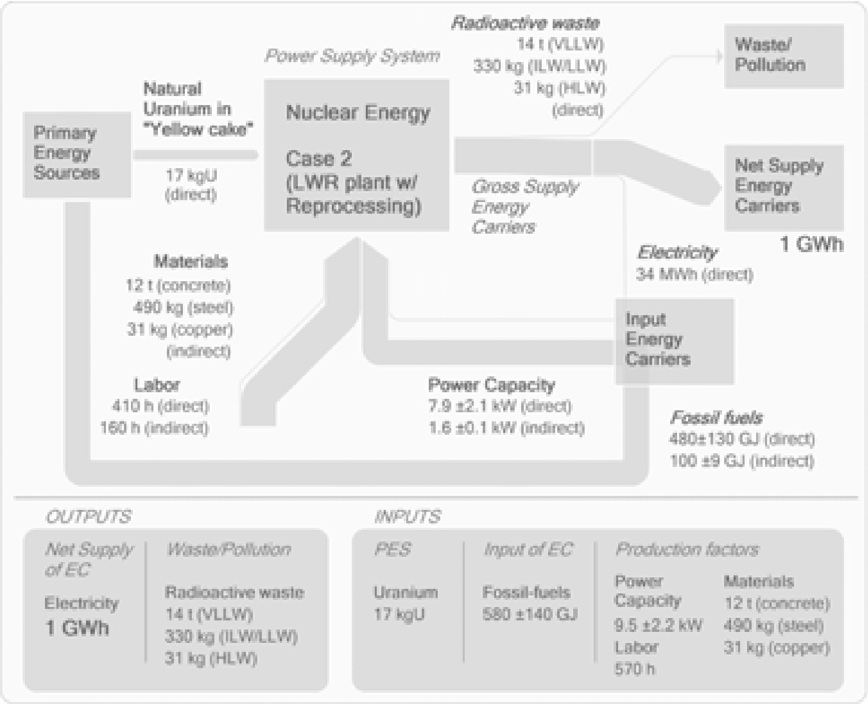
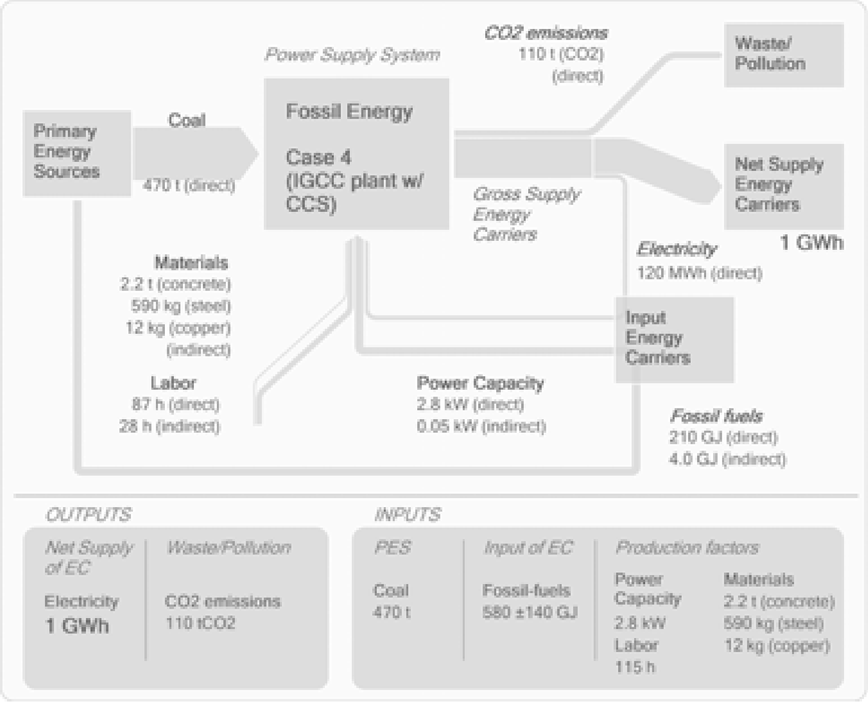


Figure 4.6 Comparison of the performance of nuclear energy and fossil energy.


Radioactive waste
14 t (VLLW)
330 kg (ILW/LLW)
31 kg (HLW)
(direct)
Power Supply System
Waste/ Pollution
Natural Uranium in "Yellow cake"
Primary Energy Sources
Nuclear Energy
Case 2 (LWR plant w/ Reprocessing)
17 kgU (direct)
Gross Supply Energy Carriers
Net Supply Energy Carriers
1 GWh
Electricity
34 MWh (direct)
Materials
12 t (concrete)
490 kg (steel)
31 kg (copper)
(indirect)
Input Energy Carriers
Labor
410 h (direct)
160 h (indirect)
Power Capacity
7.9 ±2.1 kW (direct)
1.6 ±0.1 kW (indirect)
Fossil fuels
480±130 GJ (direct)
100 ±9 GJ (indirect)
OUTPUTS
Net Supply of EC
Electricity
1 GWh
Waste/Pollution
Radioactive waste
14 t (VLLW)
330 kg (ILW/LLW)
31 kg (HLW)
INPUTS
PES
Uranium
17 kgU
Input of EC
Fossil-fuels
580 ±140 GJ
Production factors
Power Capacity
9.5 ±2.2 kW
Labor
570 h
Materials
12 t (concrete)
490 kg (steel)
31 kg (copper)


CO2 emissions
110 t (CO2)
(direct)
Power Supply System
Waste/ Pollution
Coal
Primary Energy Sources
470 t (direct)
Fossil Energy
Case 4 (IGCC plant w/ CCS)
Gross Supply Energy Carriers
Net Supply Energy Carriers
1 GWh
Electricity
120 MWh (direct)
Materials
2.2 t (concrete)
590 kg (steel)
12 kg (copper)
(indirect)
Input Energy Carriers
Labor
87 h (direct)
28 h (indirect)
Power Capacity
2.8 kW (direct)
0.05 kW (indirect)
Fossil fuels
210 GJ (direct)
4.0 GJ (indirect)
OUTPUTS
Net Supply of EC
Electricity
1 GWh
Waste/Pollution
CO2 emissions
110 tCO2
INPUTS
PES
Coal
470 t
Input of EC
Fossil-fuels
580 ±140 GJ
Production factors
Power Capacity
2.8 kW
Labor
115 h
Materials
2.2 t (concrete)
590 kg (steel)
12 kg (copper)

In the case of CO2 emissions, the fund element of the power plant refers to the structures controlling emissions after the process of production of electricity. The biophysical costs of these fund elements become significant when intending to capture most of CO2 emissions so as to prevent them from being released to the atmosphere. The controlling efforts (carbon capture) intend to ensure that the CO2 molecules will degrade into the ground before the carbon elements reach the atmosphere – a phenomenon that requires hundreds of years after injection into the ground. Nevertheless, in the case of carbon capture, the secondary trapping mechanisms (residual phase trapping, solubility trapping, mineral trapping and adsorption trapping) – that depend on chemical phenomena – rapidly take advantage over the structural and stratigraphic trapping – that requires efforts of control – after injection. This means that in the case of CO2 emissions, the time period of control is much shorter than in the case of the radioactive wastes for which handling efforts must be ensured until radioactivity drops to a level neutrally compatible with the environment.

(2) Characteristics relevant for the analysis of internal constraints (production factors)

In relation to the requirement of production factors for building and operating the power-supply system we make a distinction between the capability of handling two types of energy flow:

(i) Requirements of fossil-fuels (input of EC) for the fund elements

In relation to this indicator, the fund elements required for nuclear power-supply systems are more dependent on fossil-fuels consumption than the fund elements required for fossil energy systems. In fact they require about twice as much fossil-fuels for the making of 1GWh of electricity (360-580 GJ vs. 160-210 GJ). Moreover, this assessment can get even worse when considering the error bars for nuclear energy that are almost equal to the entire requirements for the fossil energy system (±140 GJ). This higher biophysical cost of the fund elements of the nuclear power plants (making and maintenance of facilities) is due to higher intensity of the "Generating power" unit operation of the nuclear energy system that equals the requirements of the "Mining" and "Refining" unit operations of the fossil energy system. On that respect, it should be noted that the indirect fossil-fuels requirements for the building and maintenance of fund elements of fossil energy is almost negligible when compared to nuclear energy.

(ii) Requirements of Power Capacity for the fund elements

* Direct inputs of EC (fossil-fuels) used for the generation of the gross supply of electricity – in relation to these requirements the overall PC of the power-supply system in the case of nuclear energy is about twice as much as fossil energy (4.1-7.9 kW/GWh vs. 2.6-2.8 kW/GWh). More importantly, it should be noted that the requirement of PC for fossil energy is within the same order of magnitude of the error bars for nuclear energy. This fact is determined by the higher requirements of fossil-fuels during the processes of the nuclear energy system coupled with a lower utilization factor (UF) due to less flexibility (CL) and longer unavailability periods (OL), when compared with fossil energy power plants;

* Indirect inputs of EC (fossil-fuels) used for the construction and maintenance of the fund elements of the power-supply systems – the higher amount of indirect fossil-fuels requirements translates into an indirect PC of nuclear energy that is about 2 orders of magnitude higher than for fossil energy (1.6-1.8 kW/GWh vs. 0.04-0.05 kW/GWh). This means that for making 1GWh of electricity, the nuclear-based power-supply system requires a significant capital investment (for making and maintaining the facilities) whereas it seems not to be an issue with fossil energy. In this case, the power capacity required by the fossil energy system is not even within the error bars of nuclear energy system.

(iii) Requirements of Labor (paid work) for both the flow and the fund elements

* Direct use of labor in the control of flows through the power-supply system – it is much larger in the case of nuclear energy (410-480 hours per net GWh of electricity) than for fossil energy (65-87 h/GWh). This is explained by the special characteristics of the “Mining” unit operation of the nuclear energy system being highly labor intensive.

* Indirect use of labor for the production and maintenance of fund elements – again we find values much larger with nuclear energy (about 160 h/GWh) than with fossil energy (15-28 h/GWh).

All things considered the differences in labor demand (570-640 hours found with nuclear energy versus 80-115 hours with coal-fired power plants) are quite relevant (from 5 to 8 times).

(iv) Material requirements for the production and maintenance of the fund elements

Also when looking at material requirements associated with the production and maintenance of fund elements, nuclear energy is about 5 to 8 times more intensive than fossil energy. When considering three key materials (concrete, steel and copper) we find that 13-14 tonnes vs. 1.6-2.8 tonnes are needed in order to make and maintain the facilities necessary for the power-supply systems to operate. This difference in material intensity of the structural elements explains the difference in indirect labor requirements (160 hours vs. 15-28 hours).

4.4.6 Example of an analysis referring to external constraints

As explained in sect. 4.4.3, after generating an integrated characterization of the performance of the systems per unit of output – as the one presented in fig. 4.6 – it becomes possible to perform the actual integrated assessment of the two systems in relation to different research questions. Such an integrated assessment provides a "contextualized" picture of the performance that can be used to study the severity of both external constraints and internal constraints as seen in fig. 4.1. Here we provide an example of analysis of external constraints by comparing the relative scarcity of the PES specific for the two systems (contextualizing their requirement against World coal and uranium reserves). For reason of space we consider here only one type of constraint (availability on the supply side) and only a scale of analysis (the entire World). Again we remind the reader that the main objective of this chapter is to illustrate the potentiality of our approach based on grammars and not to provide an exhaustive assessment of performance (an objective that would be impossible without having first specified the goal of the assessment). That is, the objective of our study is not to assess the quality of a specific power plant but just to illustrate the potentiality of our method to characterize the performance of energy systems in a context of energy policy choices. This means that the problem of depletion of primary energy sources (PES) becomes relevant only at the societal level. For instance, to assess the requirements of PES in a given country – associated with the adoption of a given energy system – in relation to both its domestic availability and to the risk of heavily relying on imports.

In this example, we compare the worldwide availability of uranium (PES of the nuclear energy system used in Cases 1 and 2) and coal (PES of the fossil energy system used in Cases 3 and 4) in relation to the pace of consumption of the quantity of PES which is required to generate one year of World electricity. This makes it possible to discuss the relative scarcity of the PES which the two systems depend on for their feasibility. Clearly, this analysis refers to a very large scale perspective. When adopting a different scale of analysis the criteria of contextualization could become quite different. For instance, when considering the national level an energy system may result "better" in a given country with a clear biophysical availability of the chosen PES (e.g. coal in Germany) but this assessment would not necessarily apply to a country with different PES availabilities.

The comparison of PES requirements for one year of World electricity in relation to their worldwide availability is given in fig. 4.7. In 2009, the worldwide annual electricity consumption was about 18,500TWh (OECD/IEA, 2011). Then, using the evalua-

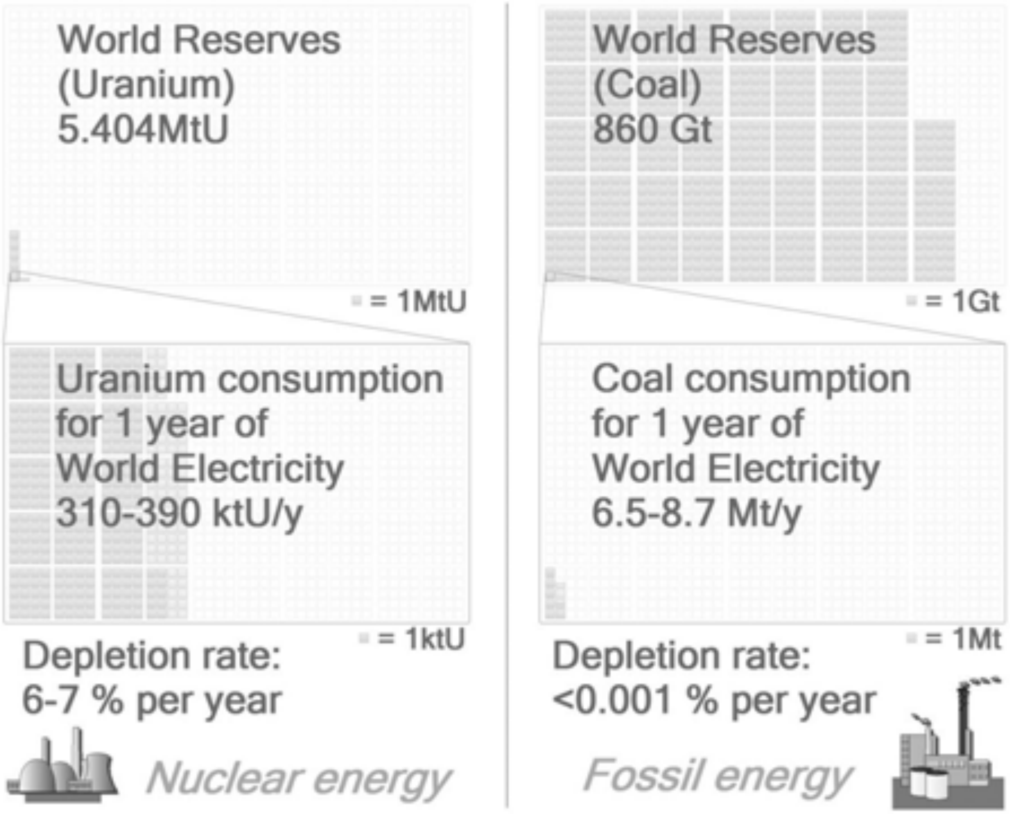


Figure 4.7 Assessment of external constraints of nuclear energy and fossil energy: PES requirements at Global level.

Source: WEC, 2010 (uranium and coal reserves excluding unconventional resources).

tion of the consumption of PES from our study (fig. 4.6), it is possible to evaluate the consumption of PES that would be necessary for supplying the worldwide electricity demand. This would translate into a consumption of PES assessed in: (i) a consumption of natural uranium of 310-390ktU/y in the case of nuclear energy; and (ii) a coal consumption of 6.5-8.7Mt/y in the case of fossil energy.

In this hypothetical example where the worldwide annual electricity consumption would have to be supplied by either only nuclear energy or only fossil energy, uranium demonstrates a higher depletion rate (6-7% per year) than coal (less than 0.001%) – about 4 orders of magnitude higher. This means that, in this context, the possibility that the availability of PES will become a limiting factor preventing the nuclear power-supply systems from supplying a significant share of the worldwide electricity demand is much stronger than for coal power-supply systems. This example of analysis in relation to external constraints (being here the availability of PES) illustrates how the given grammar can be used to discuss and compare the viability of alternative energy sources after having chosen a given narrative about the option space within which a given power-supply system can operate.

In the analysis of the possible limiting constraint on the supply side for these two types of PES, there is another significant factor that has to be considered: the change in time of their quality. Indeed, every natural resource (mineral and fossil) in a mature state of exploitation shows a declining "quality" defined as a continuous increase in mining and refining efforts – e.g. a higher requirement of production factors in our grammar – to get the same amount of fuel supplied to the power plant. In the case of nuclear energy the natural uranium shows a significant decline of its quality (Lenzen, 2008; 34] – i.e. uranium ore grade (natural enrichment) – compared with coal. This phenomenon is very important as it results in a continuous decrease in the "net supply of EC" provided by the energy system over time – the so-called 'energy cliff' (van Leeuwen, 2006) – which, especially in the case of nuclear energy, is affected by large doses of uncertainty on the actual quality of the natural resources that will be extracted in the future. As a matter of fact, it is crucial that the resource quality is systematically included in discussions about the performance of power-supply systems, and more generally of alternative (primary) energy sources.

Finally, it should be noted that in this example, we have focused on a possible analysis of limiting factors on the supply side – World availability of PES. Obviously, if we would have considered potential problems on the sink side, we should have provided a comparison of the problems associated with the generation of wastes – e.g. by comparing the negative effect of CO2 and radioactive wastes.

4.5 Conclusion

4.5.1 The peculiar characteristics of this integrated assessment

In this chapter we presented an innovative method of biophysical analysis of the characteristics of power-supply systems which is quite different in its logic from the conventional approach used in economic analysis. This fact is due to the special status of Primary Energy Sources (also called "non-manmade energy inputs"). In energetic terms we can consider the energy input provided by PES as free, as its existence does not require the use of production factors (investments of power capacity and human activity). As observed by Hall and Klitgaard *"... we do not pay Nature for energy, but only the cost of exploiting it*" (Hall and Klitgaard, 2012: 135).

For this reason, when looking at internal constraints the investments of production factors under human control refer only to the "biophysical costs" associated with the building, maintenance and operation of fund elements used in the exploitation process. That is the exploitation process can be studied by characterizing the internal loop of energy for energy, that defines (is determined by) the quality of the PES. A low quality PES can be associated with "a large requirement of energy investment under human control", also described as "a low output/input of energy carriers" and finally also described as "a low EROI (Energy Return on the Investment) of the process of exploitation". The internal loop of energy for energy in the autocatalytic loop is of crucial importance because it affects two key characteristics of the power-supply system:

(i) the requirement of fund elements (production factors) needed to control its transformation;

(ii) the requirement of PES needed to get a net supply.

This explains why the flow of coal or the flow of uranium getting into the power plant is not considered among the inputs when characterizing the energetic characteristics of the autocatalytic loop. Rather the flow of coal and uranium is considered as a flow of material input that has to be available to the system. That is, the quantitative assessment of this material flow is used to check the biophysical feasibility in relation to external constraints – i.e. tonnes consumed versus tonnes available.

On the contrary, the biophysical viability of the power-supply system in relation to internal constraints is assessed by considering energy flows, but only in terms of the flows of energy carriers. This information is then used to assess the amount of power capacity and the amount of labor required to operate the power plant. This information refers to the biophysical costs paid by society to get a net supply of energy carriers (Giampietro et al., 2011; Giampietro et al., 2012).

This peculiarity of our method of accounting implies that the biophysical analysis of performance obtained in this way generates a description of the performance of a process of production of electricity, that is non-equivalent to that provided by economic analysis. That is, this information complements that provided by economic analysis. In fact, in economic analysis the total cost of a net supply of 1 kWh of electricity is determined by:

(1) the economic cost of production factors required (technical capital, labor, and other inputs);

(2) the economic cost of the Primary Energy Sources consumed (the flow of PES);

(3) other transaction costs (e.g. administrative, security, possible liability in the case of accidents).

This economic representation can be applied to each one of the various unit operations, but it loses the holistic vision of the whole process. When assessing the economic cost of 1 tonne of PES, considered as an input to the power plant, using the price per tonne, we lose information about the technical characteristics (i.e. requirement of individual production factors) of the other unit operations – e.g. the "Mining" process. Therefore, we can no longer study the possible effects that future changes in the existing technical characteristics of the various unit operations may imply on the overall performance of the power-supply system.

4.5.2 What we can see using this approach

The approach of integrated analysis proposed here makes it possible to characterize and compare the performance of power-supply systems producing the same type of energy carrier – in the given case study nuclear energy and fossil energy used for producing electricity. The comparison can be based on an integrated set of indicators of performance (biophysical costs and benefits) chosen according to the goal of the study. To obtain this result the process of production of electricity is analyzed using a grammar defining: (i) a set of modular elements (structural and functional types); and (ii) a set of semantic and formal categories used to define the attributes of performance (fund and flow elements used to describe the network of transformations). Having organized the quantitative analysis in this way, it becomes possible to carry out an integrated assessment of the performance of power-supply systems in relation to both external and internal constraints. In this way we can characterize the option space within which a given power-supply system can operate by checking the viability of different technical options in a given situation.

For example, using the results discussed in the text we can say that:

(1) in relation to internal constraints – when considering the requirement of power capacity, human labor, and key materials (concrete, steel and copper) – the production factors making possible the system to operate – nuclear energy has a biophysical cost generally between 1 and 3 orders of magnitude higher than fossil energy. In addition, the estimates referring to nuclear energy have higher variations and a larger level of "uncertainty". This fact translates into a lower performance of nuclear energy compared to fossil energy in the supply of the same amount of electricity.

(2) in relation to external constraints – when comparing their relative scarcity of PES type – calculated by comparing the consumption of uranium and coal required for supplying the World electricity consumption of one year to the worldwide availability of the reserves of uranium and coal – nuclear energy demonstrates a natural resources depletion rate of about 4 orders of magnitude higher than fossil energy.

4.5.3 What we don't see using this approach

This approach makes it possible to characterize the performance of power-supply systems in terms of a set of biophysical indicators which can be used as benchmarks. However, the information it provides is necessary but not sufficient to characterize the viability of these systems.

First, the comparison is based on a "steady-state" narrative and therefore it does not provide information in relation to turnover times. Indeed, information like the payback time – which is extremely important for investors – would require expressing the characteristics of the power-supply systems over a larger time scale (several decades) so as to capture their overall behavior, which is not possible within the present approach. Our numbers reflect assessments averaged over one year of electricity generation.

Second, the comparison of the relative performance of the two energy systems – nuclear energy and fossil energy – is based on a definition of a grammar that looks for functional relations defining a typology of whole (the power-supply system) made of different parts (unit operations). However, in the economic representation, these different unit operations are often carried out by different economic actors that, in order to break even in economic terms, have to consider different typologies of economic costs and profits determined by the prices associated with the mix of production factors used in their operations. In order to consider the perspective of economic agents (economic viability) a complementing analysis based on an economic approach based on price is still essential.

Third, when carrying out an analysis of external constraints, in our example, we adopted a very large scale perspective (using the Global context and the average characteristics of the metabolic pattern of modern countries as a generic reference context). As mentioned earlier, a more local level (for a specific country or for a specific entrepreneur) would require developing different grammars based on a selection of other criteria and data specific for particular purposes, both in relation to the characterization of the performance of the system itself (type of reactors used in a country, etc.) and for the availability of resources (i.e. type of PES).

4.5.4 What is the beef of this approach?

As discussed in the introduction, the usefulness and effectiveness of quantitative analyses provided for governance of sustainability requires using simultaneously several non-equivalent narratives, dimensions, and scales of analysis. The biophysical approach to energy quality proposed here is based on the use of a grammar as a quantitative analytical tool capable of handling the inherent ambiguity associated with energy accounting. It characterizes the process of production of electricity in modular elements, defined using quantitative attributes referring to a given set of semantic and formal categories. In this way it becomes possible to individuate similarities and differences in the process of production of electricity, and then measure and compare “apples” with “apples” and “oranges” with “oranges”. By adopting this approach, it becomes possible to assess the quality of primary energy sources by defining the performance of power-supply systems in a multi-criteria space. For example, in our case study we found that nuclear energy demonstrates a low performance compared to fossil energy when considering the requirements of production factors for the net supply of electricity explaining the difficulties nuclear energy encounters to gain interest from investors.

This analysis of the supply side – looking at the characteristics of the processes taking place in power-supply systems within the energy sector – should be coupled to an analysis of the demand side – looking at the characteristics of the metabolic pattern of energy use in the various sectors of the economy (Giampietro et al., 2012). In any case, we believe that the case study presented in this chapter clearly illustrates that by systemically adopting a complex framework of analysis – (i) a hierarchical understanding of the functioning of energy systems through the characterization of their parts and the whole; (ii) a combination of semantic and formal categories to describe the network of energy transformations; (iii) looking at external and internal constraints using different indicators – it becomes possible to generate an integrated assessment of the overall performance of energy systems by adding more relevant information in an integrated way. In this way it becomes also possible to identify those characteristics that limit the (bio-)economic competitiveness of energy systems, a very relevant piece of information for the discussion of alternative energy sources.

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Part 3

Integrated assessment of nuclear power

Chapter 5

The viability and desirability of nuclear power in South Africa*

This chapter applies the new procedures to energy accounting developed in Chap. 3 and 4 to the case of South Africa that is currently undertaking a large-scale deployment of this technology in its mix of energy sources generating electricity. Indeed, the case of the South Africa's emerging economy provides a very good exercise for checking the feasibility, viability and desirability of nuclear power against external and internal constraints to the energetic metabolism of this country. The other purpose of this practical application is to check the robustness and usefulness of the new procedures to energy accounting developed in this thesis.

> *Regardless of the various definitions of 'renewable', nuclear power therefore meets every reasonable criterion for sustainability, which is the prime concern.*
>
> —World Nuclear Association (June 2013)

In its attempt to promote nuclear power as a viable energy source, the nuclear industry has been using the narrative of sustainability to refer to this energy source since the early 2000s (see Chap. 6). Here I challenge this narrative by deconstructing the "every-reasonable-criterion-for-sustainability" mindset on the basis that (1) on the normative side – such claim must be used in a context as sustainability cannot be defined in absolute terms; and (2) on the descriptive side – the selection of criteria and representation framework used to assess the viability of a given energy source must

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result from their relevance and usefulness within the scientific output generated, not from a deliberate choice of one specific perception over the meaning of sustainability.

5.1 The energy situation in South Africa

5.1.1 Energy policy landscape

Reducing 'energy poverty' is becoming one of the most pressing priorities at the international level to the extent that it is recognized as the 'missing development goal' by the FAO (2012). As a matter of fact the issue of energy access is under increasing scrutiny at the energy policy level (Srivastava and Sokona, 2012). This is the case for instance of most countries in Southern Africa where electrification rates are low (e.g. 34% and 45% in Namibia and Botswana respectively in 2011), although the situation in the region is very unequal with electrification rates ranging from 9% in Malawi to more than 90% in South Africa (Hailu, 2012). To address the problem of energy access, concerned countries have therefore set advanced country- and regional-level energy access targets, with a number of them putting forth 100% access targets in electrification, modern fuels and/or mechanical power. In the case of South Africa, the government set in 2004 a 100% electrification target by the end of 2012 (Bekker et al., 2008). The latest estimations however indicate that this target has not been reached (Makonese et al., 2012), and that at current rate of electrification, it may take South Africa 20 years more before it achieves “universal access” to basic electricity for all its citizens (Infrastructure News, 9 October 2012).

In addition, South Africa like any rapidly developing countries is facing energy efficiency constraints as their energy systems are mostly based on conventional non-renewable energy resources. The country is Africa's largest generator of GHG emissions and ranks among the 10 countries with worse “carbon footprint” in the world. To correct this situation, the government has engaged a “new energy deal” to improve by 15% the energy efficiency with respect to its current consumption, while introducing the generation of up to 16% of primary energy supply from renewable sources by 2025 (Spanish Embassy in South Africa, 2011).

Aggressive targets on both energy access and energy efficiency imply a situation of forced energy transition in South Africa. To worsen the situation, there are claims that conventional energy technologies and deployment approaches will not eliminate energy poverty in Africa (Agbemabiese et al., 2012). For this reason, the renewable energy market in the Southern Africa region has recently seen a great influx of foreign companies. For instance, Spanish companies have been awarded 42% of the contracts, tendered by the government, for the provision of renewable energy in South Africa. This explains why South Africa is Africa's first country in terms of UN's Clean Development Mechanism (CDM) project by covering 25% of all projects in the region.

However, the development of renewable energy technology in South Africa 'per se' does not guarantee that these resources are properly used to develop energy systems that are equally accessible to all social actors involved in an environmental friendly way. Risks are that many of these technologies may remain as costly gadgets unused in the daily life of the people they intend to help. For this reason, it is essential that societies undergoing an energy transition have available effective methods of analysis and procedures of governance. In fact, according to energy experts in the region, South Africa like other countries whose States have adopted energy access targets – hence, where it is possible to measure and monitor progress towards these goals – energy policies become more relevant (Hailu, 2012). Nevertheless, conventional indicators or metrics are not able to capture progress on energy access since this analysis would require considering simultaneously multiple dimensions (Bhanot and Jha, 2012). Yet, no efforts are made in the direction of developing more effective integrated analysis. For this reason, it is crucial for the region, and for South Africa in particular, to develop the expertise capable of generating coherent and holistic assessment methods and governance procedures across different scales.

To worsen the situation, energy efficiency and energy access are intertwined in a nexus involving energy, water, food as well as land-use. For instance, the current dependence of the food-supply system on fossil-fuels consumption – the food sector using approximately 30 percent of the global energy consumption – makes it vulnerable to the fluctuating and rising fossil-fuels prices. Unfortunately, linkages between energy-supply, food-supply and water-supply systems have now been recognized as one of the planet's most pressing development challenges to the extent that the Academy of Science of South Africa has recently signed a joint declaration – along with 14 other national science academies – calling world leaders to "ensure that programs in energy and water are fully integrated and that solutions are developed with a systems approach that takes into account their interdependencies" and to "establish effective governance structures and clear policies to facilitate the integrated management of energy, water, and agriculture systems" (G-Science Academies, 2012).

One concrete consequence of those complex relationships is that the growing dependence of modern industrial societies on fossil fuels determined by the unstoppable economic growth of emergent countries like China, India, Brazil as well as South Africa will drive the cost of fossil energy up in the future, as it has already been the case in the mid-2000s. This trend will progressively worsen the situation of the most vulnerable communities by preventing them from accessing energy, and ultimately, from achieving sufficient food, water and energy services. For this reason, it is essential to learn, as soon as possible, how to decouple the food-supply systems from fossil-fuels consumption and to address the complex links between food security and energy security in relation to the availability and use of natural resources (especially water and land). Such a task requires a redefinition of the use of science for informed decision making when dealing with complex issues. More and more the simplistic analysis of reductionism, based on the adoption of a scale at the time, proves to be ineffective to deal with problems that must be analyzed by considering simultaneously several dimensions of analysis and several scales (micro, meso, macro, the whole planet) at the same time.

5.1.2 Deployment of nuclear power

In such a context of a growing economy there have been prospects of large-scale deployment of nuclear power in South Africa. The use of nuclear energy for generating electricity in South Africa started in 1999 under the Nuclear Energy Act, 1999 (Act No. 46 of 1999) (see SA Government, 1999), although the extraction of uranium for exports started much before – uranium production ("yellow cake", U_3O_8) peaked at 6.1 ktons per year in 1981 (Dittmar, 2011; 2013). Currently there are two nuclear reactors operating in South Africa totalizing 1800 MW of installed capacity and located in Koeberg in the coastal region of Cape Town (see also fig. 5.4).

In 2010, the South African Department of Energy (SA DOE) enacted a new energy act in which they explored the possibility of deploying further nuclear power in the country (SA DOE, 2011):

> *The scenarios indicated that the future capacity requirement could, in theory, be met without nuclear, but that this would increase the risk to security of sup-*

> *ply (from a dispatch point of view and being subject to future fuel uncertainty). […] Three policy choice options were identified: a) Commit to the nuclear fleet as indicated in the RBS; b) Delay the decision on the nuclear fleet indefinitely (and allow alternatives to be considered in the interim); c) Commit to the construction of one or two nuclear units in 2022-4, but delay a decision on the full nuclear fleet until higher certainty is reached on future cost evolution and risk exposure both for nuclear and renewables.*
>
> (SA DOE, 2011: 14, art. 4.2 and 4.3)

It should be noted however that none of these scenarios consider the costs of decommissioning nuclear power plants and handling radioactive waste – that are however two essential processes of energy supply systems required for reproducing the funds and flows respectively (see Chap. 4):

> *Further research is required on the full costs relating to specific technologies (coal and nuclear) around the costs of decommissioning and managing waste (in the case of nuclear specifically spent fuel).*
>
> (SA DOE, 2011: 25, art. 7.11)

In 2011, it was announced that the Department accepted the above described option (a) of committing to a full nuclear fleet of 9,600 MW of new installed capacity for nuclear power – in order to achieve a total generating capacity of 11,400 MW by 2030 – under the narrative that*: "this should provide acceptable assurance of security of supply in the event of a peak oil-type increase in fuel prices and ensure that sufficient dispatchable base-load capacity is constructed to meet demand in peak hours each year."* (SA DOE, 2011: 14, art. 4.4)

The following sections attempt to provide a quality control over this narrative by checking the biophysical constraints implied by this deployment plan.

5.2 Diagnostic analysis of the South African energy sector

In this section, I perform the diagnostic analysis of the exosomatic energy flows of South Africa for the year 2009 – hence, before the new deployment plan of nuclear power was enacted by the government – following the procedures for the formalization of the energy grammar presented in Chap. 3. For this purpose, the following sections focus on the direct application of the procedures while details on the typologies of data (entry points) and steps of analysis (logical framework) used in this application will be found in Appendix II.

5.2.1 The energy grammar applied to South Africa

As this case study focuses on the assessment of the quality of primary energy sources (PES) and the process of production of energy carriers (EC), we single out the energy sector as the hypercyclic compartment of society in charge for the production of energy carriers (see the "standard" grammar for the analysis of the metabolic pattern of energy detailed in Chap. 3).

** when adopting the external view* – we can define the requirement of a gross supply that must be made available by using primary energy sources by: (i) the hypercyclic part (Energy & Mining) – that is local production of energy carriers (LOCAL); plus (ii) imports (IMPER and IMPEC).

** when adopting the internal view* - we can define the requirement of energy carriers in society – when looking at the metabolic flow from the consumption side - as determined by the sum of: (i) the Net Supply of Energy Carriers – the specific consumption of energy carriers of the various compartments of the society (indicated by the vectors of end-uses) divided in a purely dissipative part (energy is used to express functions outside the energy sector); and hypercyclic part (the energy used in the energy sector); (ii) the exports; and (ii) the losses.

In our analysis we have to address quantitative analysis based on the adoption of both the external and internal views about the system. As a matter of fact, when checking the feasibility in relation to external constraints – i.e. the availability of enough primary energy sources – the required information can only be assessed using a scalar-based representation of energy flows and fund elements referring to the external view (tab. 5.1). When checking the viability of the consumption of energy carriers as well as other flows in relation to internal constraints, the required information can only be assessed using a scalar-based representation by means of a multi-dimension/multi-scales matrix (tab. 5.2). Then, when checking the viability of the production of energy carriers in relation to internal constraints – i.e. the strength of the hypercycle generating more energy carriers than those used per unit of production factor – the required information can only be assessed using a vector-based representation of energy flows and fund elements referring to the internal view (tab. 5.3).

Table 5.1. Diagnostic analysis of the energetic metabolism of South Africa (year 2009) – Scalar-based representation of the energy flows and fund elements (external view).

BENCHMARKS*	**FLOW**	**FUND**		
	ENERGY (PJ-GER)	**THA (Ghr)**	**TPCD (GW-REU)**	**TPCH (GW-GSEC)**
TOTAL ENERGY THROUGHPUT (TET)	8,140	450	750	260
IMPORTS as GER (IMPER)	1,210			
IMPORTS as EC (IMPEC)	380			
DOMESTIC SUPPLY (LOCAL)	6,550			

**: numbers may not add up due to rounding.*

Table 5.2 Diagnostic analysis of the nexus assessment of South Africa – Scalar-based representation of the flows and funds using a multi-level/multi-dimensional matrix (internal view).

	FLOWS*				**FUNDS***		
CONSUMPTION SIDE	**FOOD (PJ-NFS)** (a)	**ENERGY (PJ-GER)** (b)	**WATER (hm3-GWR)** (a)	**VALUE ADDED (billion US$)**(a)	**HUMAN ACTIVITY (Ghr)** (a)	**POWER CAPACITY DISSIPATIVE (GW-REU)** (b) (a)	**LAND USE (10^6 ha)**
WHOLE (n)	**330**	**6,500**	**41,000**	**330**	**450**	**750**	**100**
DISSIPATIVE part (n-1)	*230*	*6,400*	*39,000*	*290*	*450*	*750*	*100*
HYPERCYCLE (n-1)	*N/A*	*110*	*890*	*37*	*0.46*	*2.7*	*negl.*
LOSSES (n)	**100**	**240**	**790**	**N/A**	**N/A**	**N/A**	**N/A**
EXPORTS (n)	**-61**	**-1,400**	**-9,000**	**76**	**N/A**	**N/A**	**N/A**

SUPPLY SIDE	IMPORTS	62	1,600	11,000	-76	N/A	N/A	N/A
	EM sector	N/A	6,500	N/A	N/A	N/A	N/A	N/A

*Notes: (a) Year 2010, source: Giampietro et al. (eds.), in press; (b) Year 2009, own elaboration. *: numbers may not add up due to rounding.*

Table 5.3 Diagnostic analysis of the energetic metabolism of South Africa (year 2009) – Vector-based representation of the energy flows and fund elements (internal view).

	FLOWS*		**FUNDS***		
CONSUMPTION SIDE	**ET-t (PJ-EC)**	**ET-m (PJ-EC)**	**HA (Ghr)**	**PCD-t (GW-REU)**	**PCD-m (GW-REU)**
WHOLE (n)	**4,400**	**790**	**450**	**350**	**400**
DISSIPATIVE part (n-1)	*4,300*	*790*	*450*	*340*	*400*
HYPERCYCLE (n-1) [(a)]	*100*	*4*	*0.46*	*2.6*	*0.13*
LOSSES (n)	**0**	**92**	**N/A**	**N/A**	**N/A**
EXPORTS (n)	**-1,200**	**-50**	**N/A**	**N/A**	**N/A**
SUPPLY SIDE					
IMPORTS	1,400	52	N/A	N/A	N/A
EM sector	4,200	880	N/A	N/A	N/A

*Notes: (a) HYPERCYCLE corresponds to the consumption of production factors within the Energy and Mining (EM) sector. *: numbers may not add up due to rounding.*

Then, as explained in Chap. 3, when focusing on the energy supply sector, the vector referring to the energy supply sector (raw “HYPERCYCLE (n-1)” in tab. 5.3) can be extended to a matrix-based representation of flows and funds at the interface of the two internal – the processes taking place within the energy and mining sector requiring the use of production factors – and external views – the set of locally available primary energy sources exploited in the energy sector of South Africa (tab. 5.4).

That is, the change of perspective, from the external to the internal view, implies switching from numbers organized in ‘scalars’ to numbers organized in ‘vectors’ in the quantitative representation. That is Gross Energy Requirements are scalar quantities measured in GER-thermal joules (e.g. Tons of Oil Equivalent), whereas if we want to describe the use of Energy Carriers inside the society, we have to use vectors describing different quantities of energy referring to different typologies of EC, all measured in joules – i.e. J of electricity (mechanical energy), J of fuels (chemical potential energy) and J of heat (thermal energy) – Giampietro et al., 2012.

Table 5.4 Diagnostic analysis of the energetic metabolism of South Africa (year 2009) – Opening the energy supply vector using a matrix-based representation of the energy flows (interface external/internal views).

EM sector	**Consumption of production factors**					**Supply of Energy Carriers**	
	HA (Mhr)	**ET-t (PJ-EC)**	**ET-m (PJ-EC)**	**PCD-t (MW-REU)**	**PCD-m (MW-REU)**	**NSEC-t (PJ-EC)**	**NSEC-m (PJ-EC)**
EM (n-1)	**460**	**100**	**4.2**	**2,600**	**130**	**5,600**	**850**
PHYSICAL GRADIENTS (n-2)	***430***	***100***	***4.2***	***2,600***	***130***	***4,200***	***800***
Fossil fuels (n-3)	150	37	2.6	370	84	3,600	750
Nuclear (n-3)	12	3.2	1.5	32	48	-	42
Biofuels (n-3)	270	60	negl.	2,200	negl.	600	3.4
Others (n-3)	negl.	negl.	negl.	negl.	negl.	negl.	5.9
IMPORTS as GER (n-2)	***35***	***0.85***	***0.03***	***9.2***	***0.8***	***1,200***	***7.2***
Fossil fuels (n-3)	35	0.85	0.03	9.2	0.8	1,200	7.2
IMPORTS as EC (n-2)	***negl.***	***negl.***	***negl.***	***negl.***	***negl.***	***260***	***40***

Fossil fuels (n-3)	negl.	negl.	negl.	negl.	negl.	260	negl.
Electricity (n-3)	negl.	negl.	negl.	negl.	negl.	-	40

**: numbers may not add up due to rounding.*

By looking at tab. 5.4, we see that nuclear power currently generates about 5% (42 PJ-EC or 13 TWh) of the overall electricity supply (850 TJ-EC or 260 TWh) every year. Hence, nuclear power does not appear as a significant energy source in the current energy mix of South Africa.

It should be recalled here that according to the first law of thermodynamics energy cannot be created. Therefore, by definition, primary energy sources must be favorable physical gradients provided by boundary conditions (by processes taking place outside human control) available to humans. These favorable boundary conditions enable the production of a net supply of energy carriers. This is what requires a check in relation to the external view. Moreover, thermodynamics also tells us that different energy forms do have different qualities and their conversion is subject to thermodynamic principles. We cannot sum 1 Joule of electricity to 1 joule of heat and we have to consider very carefully conversion factors when accounting energy transformations within complex networks.

In the PES/EC supply matrix shown in tab. 5.4, we assess: (i) the relative contribution of each energy source in relation to the total net supply of energy carriers in the EM sector (on the last two columns on the right); and (ii) the relative consumption of energy carriers (in the column ET-t and ET-m). In this way, it becomes possible to establish a relation between the overall characteristics of the EM sector – using a vector: EM (n-1) – and the characteristics of its subparts – using a matrix: Physical Gradients (n-2). In particular, we distinguish three main categories of energy products at level n-2: (1) Physical gradients, which correspond to the domestic supply of primary energy sources (LOCAL); (2) Imports as GER-thermal (IMPER), which correspond to the imported products used for making energy carriers (e.g. coal or fuel to power plants or refineries); and (3) Imports as energy carrier (IMPEC), which correspond to the import of energy products that are used directly as energy carriers (e.g. petroleum products or electricity with no conversion losses).

The energy supply matrix is useful to identify the profiles of use of production factors (labor and power capacity) and the requirement of energy carriers required for the exploitation of different types of primary energy sources. The combination of the characteristics of the various vectors of the matrix (determined by the relative contribution of each energy source) define the overall consumption of production factors and energy carriers that society has to invest in the energy & mining sector (EM) to generate its internal gross supply of energy carriers.

5.2.2 Formal relations representing the energy flows

The following figures apply the set of formal relations linking the different energy flows based on vectors and matrices provided in Chap. 3 to the case of South Africa, for the year 2009. In particular, (1) fig. 5.1 links Energy Carriers (expressed in J-EC) to the most significant Primary Energy Sources (expressed in J-GER) on the supply side (external view, equ. (1) of Chap. 3); fig. 5.2 links End Uses (measured in J-EC) to Energy Carriers (expressed in J-EC) on the consumption side (internal view, equ. (2) of Chap. 3), and fig. 5.3 links Primary Energy Sources to End Uses by mapping the supply of EC generated by every PES to the consumption of EC by every End Use (external-internal bridge, equ. (3) of Chap. 3).

equ. (1): $GSEC_{i,j} \times (GER/GSEC)_j = GER_i$

(South Africa, 2009)

$$
\begin{array}{rcc}
 & \textit{thermal} & \textit{mechanical} \\
\textbf{EM (n-1)} & \mathbf{5{,}590} & \mathbf{937} \\
\textbf{PHYSICAL GRADIENTS (n-2)} & \mathbf{4{,}159} & \mathbf{884} \\
\textit{All Fossil fuels (n-3)} & 3{,}556 & 828 \\
\textit{Nuclear Power (n-3)} & 0 & 46 \\
\textit{Biofuels (n-3)} & 600 & 4 \\
\textit{Others (n-3)} & 2 & 7 \\
\textbf{IMPORTS AS GER (n-2)} & \mathbf{1{,}167} & \mathbf{8} \\
\textit{All Fossil fuels (n-3)} & 1{,}167 & 8 \\
\textbf{IMPORTS AS EC (n-2)} & \mathbf{264} & \mathbf{44} \\
\textit{All petroleum products (n-3)} & 264 & 0 \\
\textit{Electricity (n-3)} & 0 & 44
\end{array}
\times
\underbrace{\begin{bmatrix} 1.02 \\ 2.61 \end{bmatrix}}_{\substack{\textbf{Conversion} \\ \textbf{factors}}}
=
\underbrace{\begin{bmatrix} \mathbf{8{,}140} \\ \mathbf{6{,}550} \\ 5{,}800 \\ 120 \\ 620 \\ 20 \\ \mathbf{1{,}210} \\ 1{,}210 \\ \mathbf{380} \\ 270 \\ 120 \end{bmatrix}}_{\substack{\textbf{Gross Energy} \\ \textbf{Requirement} \\ \textbf{(PJ-GER)}}}
$$

$$\substack{\textbf{Gross Supply of} \\ \textbf{Energy Carriers} \\ \textbf{(PJ-EC)}}$$

Figure 5.1 Linking Energy Carriers to Primary Energy Sources on the supply side (external view) – Diagnostic analysis of South Africa, year 2009.

Note: numbers may not add up due to rounding.

$$\text{equ. (2):}\qquad REUD_{k,j} + HYPERCYCLE_{k,j} + LOSSES_{k,j} + EXPORTS_{k,j} = GSEC_{k,j}$$

(South Africa, 2009)

$$\begin{array}{r} \\ \textbf{WHOLE (n)} \\ \textit{DISSIPATIVE (n-1)} \\ \textit{HYPERCYCLE (n-1)} \\ \textbf{LOSSES (n)} \\ \textbf{EXPORTS (n)} \end{array}
\underset{\substack{\textbf{Requirement}\\ \textbf{of End Uses}\\ \textbf{Dissipative*}}}{\begin{array}{c} \begin{array}{cc} \textit{thermal} & \textit{mechanical} \end{array} \\ \left(\begin{array}{cc} \mathbf{4,251} & \mathbf{790} \\ 4,251 & 790 \\ 0 & \\ \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{array}\right) \end{array}}
+
\underset{\substack{\textbf{Hypercycle*}\\ \textbf{(conversion losses)}}}{\begin{array}{c} \begin{array}{cc} \textit{thermal} & \textit{mechanical} \end{array} \\ \left(\begin{array}{cc} \mathbf{101} & \mathbf{4} \\ 0 & 0 \\ 101 & 4 \\ \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{array}\right) \end{array}}
+
\underset{\substack{\textbf{Distribution}\\ \textbf{losses*}}}{\begin{array}{c} \begin{array}{cc} \textit{thermal} & \textit{mechanical} \end{array} \\ \left(\begin{array}{cc} \mathbf{0} & \mathbf{0} \\ 0 & 0 \\ 0 & 0 \\ \mathbf{0} & \mathbf{92} \\ \mathbf{0} & \mathbf{0} \end{array}\right) \end{array}}$$

$$+
\underset{\textbf{Exports*}}{\begin{array}{c} \begin{array}{cc} \textit{thermal} & \textit{mechanical} \end{array} \\ \left(\begin{array}{cc} \mathbf{0} & \mathbf{0} \\ 0 & 0 \\ 0 & 0 \\ \mathbf{0} & \mathbf{0} \\ \mathbf{-1,242} & \mathbf{-50} \end{array}\right) \end{array}}
=
\underset{\substack{\textbf{Gross Supply of}\\ \textbf{Energy Carriers*}}}{\begin{array}{c} \begin{array}{cc} \textit{thermal} & \textit{mechanical} \end{array} \\ \left(\begin{array}{cc} \mathbf{4,352} & \mathbf{794} \\ 4,251 & 790 \\ 101 & 4 \\ \mathbf{0} & \mathbf{92} \\ \mathbf{-1,242} & \mathbf{-50} \end{array}\right) \end{array}}$$

**: in PJ-EC*

Figure 5.2 Linking End Uses to Energy Carriers on the consumption side (internal view) – Diagnostic analysis of South Africa, year 2009.

Note: numbers may not add up due to rounding.

$$\text{equ. (2):} \quad REUD_{k,j} + HYPERCYCLE_{k,j} + LOSSES_{k,j} + EXPORTS_{k,j} = GSEC_{k,j}$$

(South Africa, 2009)

$$
\begin{array}{r}
\textbf{WHOLE (n)} \\
\textit{DISSIPATIVE (n-1)} \\
\textit{HYPERCYCLE (n-1)} \\
\textbf{LOSSES (n)} \\
\textbf{EXPORTS (n)}
\end{array}
\underset{\substack{\textbf{Requirement} \\ \textbf{of End Uses} \\ \textbf{Dissipative*}}}{\overset{\begin{array}{cc}\textit{thermal} & \textit{mechanical}\end{array}}{\begin{pmatrix}
\mathbf{4,251} & \mathbf{790} \\
4,251 & 790 \\
0 & \\
\mathbf{0} & \mathbf{0} \\
\mathbf{0} & \mathbf{0}
\end{pmatrix}}}
+
\underset{\substack{\textbf{Hypercycle*} \\ \textbf{(conversion losses)}}}{\overset{\begin{array}{cc}\textit{thermal} & \textit{mechanical}\end{array}}{\begin{pmatrix}
\mathbf{101} & \mathbf{4} \\
0 & 0 \\
101 & 4 \\
\mathbf{0} & \mathbf{0} \\
\mathbf{0} & \mathbf{0}
\end{pmatrix}}}
+
\underset{\substack{\textbf{Distribution} \\ \textbf{losses*}}}{\overset{\begin{array}{cc}\textit{thermal} & \textit{mechanical}\end{array}}{\begin{pmatrix}
\mathbf{0} & \mathbf{0} \\
0 & 0 \\
0 & 0 \\
\mathbf{0} & \mathbf{92} \\
\mathbf{0} & \mathbf{0}
\end{pmatrix}}}
$$

$$
+
\underset{\textbf{Exports*}}{\overset{\begin{array}{cc}\textit{thermal} & \textit{mechanical}\end{array}}{\begin{pmatrix}
\mathbf{0} & \mathbf{0} \\
0 & 0 \\
0 & 0 \\
\mathbf{0} & \mathbf{0} \\
\mathbf{-1,242} & \mathbf{-50}
\end{pmatrix}}}
=
\underset{\substack{\textbf{Gross Supply of} \\ \textbf{Energy Carriers*}}}{\overset{\begin{array}{cc}\textit{thermal} & \textit{mechanical}\end{array}}{\begin{pmatrix}
\mathbf{4,352} & \mathbf{794} \\
4,251 & 790 \\
101 & 4 \\
\mathbf{0} & \mathbf{92} \\
\mathbf{-1,242} & \mathbf{-50}
\end{pmatrix}}}
$$

**: in PJ-EC*

Figure 5.3 Linking Primary Energy Sources to End Uses (external-internal bridge) – Diagnostic analysis of South Africa, year 2009.

Note: numbers may not add up due to rounding.

This set of information generated is not directly used in this diagnostic analysis, but makes it possible to summarize information in relation to energy flows at multiple scales. However, this information is useful for keeping congruence across scales and among energy forms when generating scenarios.

5.3 Integrated assessment of the viability and feasibility of nuclear power in South Africa

In this simulator analysis we consider the potential and trade-offs of using nuclear power to replace fossil energy sources following the "2010-2030 deployment plan" proposed by the South African government (see sect. 5.1.2). This scenario can be summarized by the following target of new installed capacity by 2030 (SA DOE, 2011):

- New installed capacity between 2010 and 2030: 9,600 MW;
- Total generating capacity by 2030: 11,400 MW.

This deployment plan would make nuclear power becoming a significant energy source in the energy mix of South Africa by increasing from 5% (42 PJ-EC or 13 TWh, see tab. 5.3) to 24% (260 PJ-EC or 79 TWh, see tab. 5.8) of the total electricity supply, hence the adjective "large-scale" qualifying this deployment plan.

5.3.1 Technical coefficients of nuclear power in South Africa

According to the Red Book which provides information about worldwide uranium supply (OECD/IAEA, 2010), South Africa currently has the facilities to manage the full nuclear fuel cycle of the nuclear energy system, except reprocessing facilities.

The current situation of the "nuclear energy system" in South Africa can be characterized in relation with the four standard unit operations of energy supply systems (see Chap. 4):

(1) Mining – South Africa contains the facilities (funds) required to make and maintain the flows (uranium resources);

(2) Refining/Enriching – South Africa contains the facilities to enrich the uranium in the form of "yellow cake" (U_3O_8) and to process nuclear fuel ready to be loaded into their nuclear reactors. Note that the technical coefficients evaluated in Chap. 4 do not include the biophysical costs of transportations of uranium resources (mining process) and nuclear fuel (enriching process) as those costs would be negligible in the case of South Africa. In fact, South Africa currently has the capability to supply all nuclear fuels from domestic supply as it includes the facilities requires in the front-end processes (mining and enriching unit operations). It should be noted that South Africa is one of the very few countries to be in this situation worldwide, as most countries are importing either "yellow cake" (e.g. France) or nuclear fuel ready to be used in their reactors (e.g. Spain).

As a matter of fact, the biophysical costs of building and running further mining and enrichment facilities are also included in the scenario of a large-scale deployment of nuclear power in South Africa in order to meet the increase in the consumption of nuclear fuels. Under this scenario, South Africa would therefore continue to require only regional transportation for its nuclear fuel cycle which can be considered as negligible or at least comparable to the case of the coal-based power-supply system;

(3) Generating power – South Africa currently has two nuclear reactors (2 x 900 MW) totalizing an installed power capacity of 1,800 MW; and

(4) Handling waste / Controlling pollution – South Africa does not have the storage facilities (funds) required for the long-term management of radioactive waste (flows or funds depending on the time scale, see Chap. 3), nor the plant for reprocessing used nuclear fuel. The country currently is temporary storing high-level radioactive waste on-site in storage pools inside the power plant at Koeberg and sends other radioactive waste to another storage facility in Vaalputs in the Northern Cape region.

The narrative of the 2010-2030 deployment plan set by the government referring to security of energy supply requires to handle the whole process of production. For this reason, the case considered in this scenario will account for the investment of production factors required to handle the four above mentioned unit operations with the exception of the reprocessing activities (see case "Nuclear Energy without Reprocessing" detailed in Chap. 4). Tab. 5.5 and 5.6 summarize the technical coefficients of this case.

Table 5.5 Supply and consumption of energy flows from the nuclear energy system in South Africa – direct requirements for the making and maintenance of flows.

GSEC (GWh/MW)	**PES (kgU/GWh)**	**ET-THERMAL (GJ-EC/GWh)**	**ET-MECHANICAL (GJ-EC/GWh)**
6.9	21	250	119

Source: after case "Nuclear Energy without Reprocessing" in Diaz-Maurin and Giampietro, 2013; (see also Chap. 4).

Table 5.6 Consumption of production factors from the nuclear energy system in South Africa – direct requirements for the making and maintenance of flows.

PCD-THERMAL (kW-REU/GWh)	PCD-MECHANICAL (kW-REU/GWh)	HA (hr/GWh)	WT (m3/GWh)	LU (ha/GWh)
2.5	3.8	480	3,100	negl.

Sources: own elaboration (for PCD); after case "Nuclear Energy without Reprocessing" in Diaz-Maurin and Giampietro, 2013 (see also Chap. 4) (for HA); after EPRI, 2010 (for WT).

According to tab. 5.5, nuclear power would generate about 24% (260 PJ-EC or 79 TWh) of the overall electricity supply (850 TJ-EC or 260 TWh, see tab. 5.4) under this scenario every year.

The technical coefficients presented in tab. 5.5 and 5.6 both refer to the direct requirements for the making and maintenance of energy flows used in the three assessments of the feasibility, viability and desirability of the nuclear power deployment plan in South Africa. That is, they disregard the investment of production factors required for reproducing the funds (facilities) used only for the assessment of the viability against internal constraints – i.e. availability of production factors required for making and maintaining the new installed capacity.

5.3.2 Feasibility assessment against external constraints

This section provides an assessment of the feasibility of the 2010-2030 deployment plan of nuclear power in South Africa against three sets of external constraints in relation with the supply side and the sink side.

(1) Spatial constraints on the supply side

Looking at the spatial constraints for the deployment of nuclear power plants we see that the coastal areas – areas where there is no constraints of water withdrawal for cooling system – are densely populated, which poses the problem of settling the new nuclear plants (see fig. 5.4).

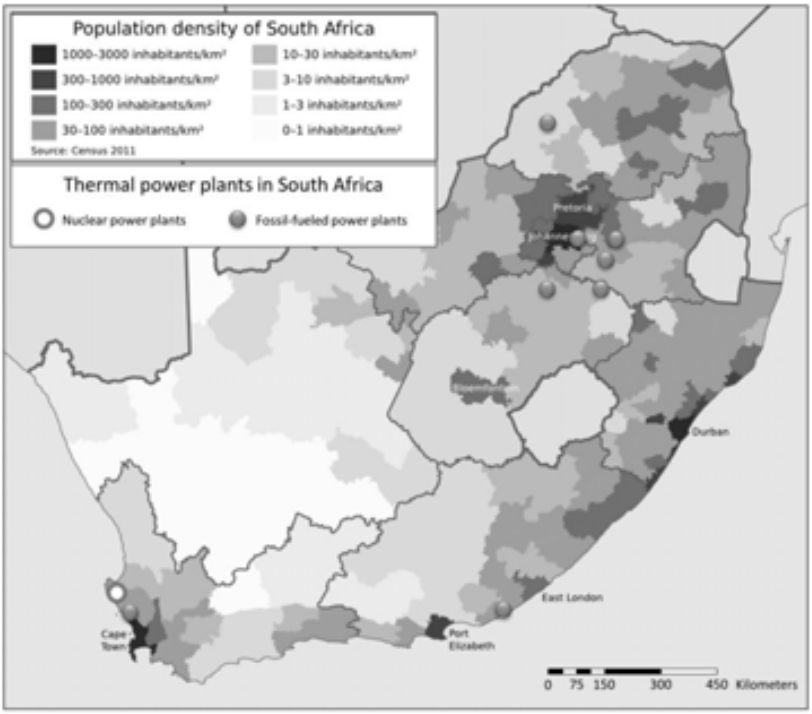

Figure 5.4 GIS-based integrated analysis of spatial constraints to energy supply in South Africa: location of current power plants vs. population density.

Source: own elaboration.

According to the previous figure, the only location where there is a low density of population corresponds to the Northern Cape Province of South Africa, a desert region where there is very low water availability and high solar irradiation (hence a high potential for solar energy) as shown in fig. 5.5 and 5.6.

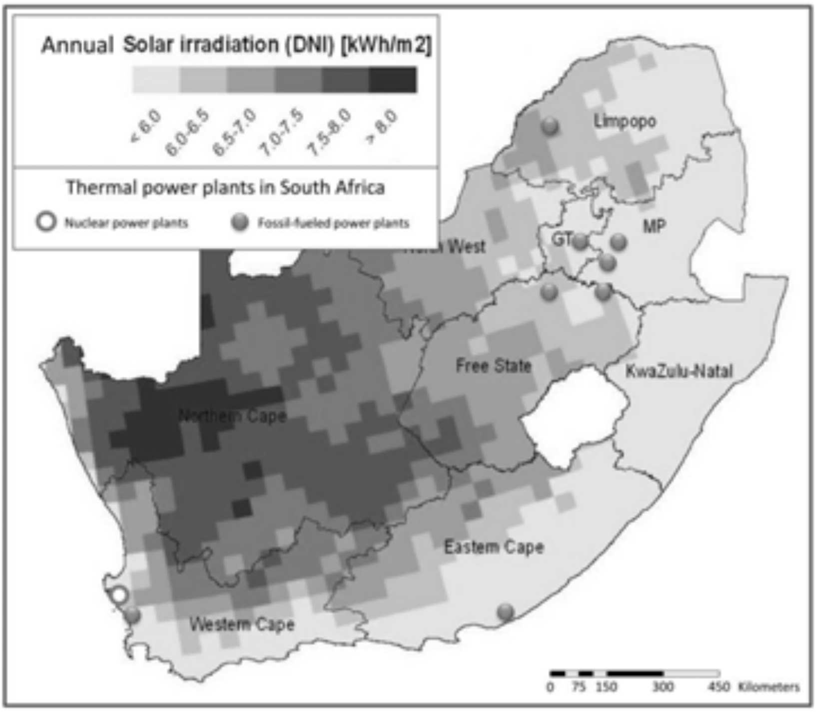

Figure 5.5 GIS-based integrated analysis of spatial constraints to energy supply in South Africa: location of current power plants vs. annual solar irradiation.

Source: own elaboration.

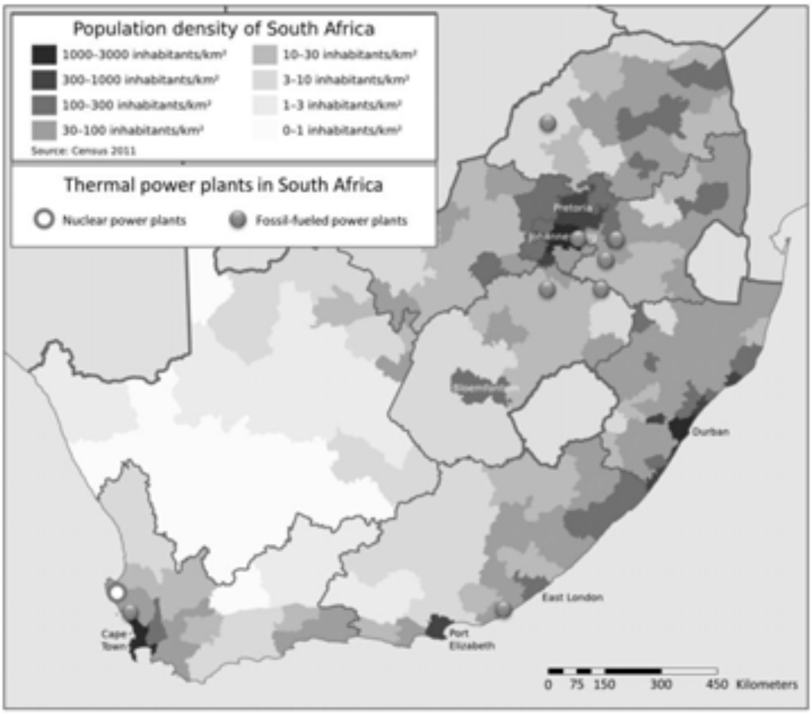

Figure 5.6 GIS-based integrated analysis of spatial constraints to energy supply in South Africa: location of current power plants vs. annual precipitations and irrigated areas.

Source: elaboration by T. Serrano and F. Diaz-Maurin.

(2) Availability of primary energy sources (uranium) on the supply side

Uranium production in the form of yellow cake U_3O_8 – the Primary Energy Source of the nuclear energy system being a sub-product of the Mining unit operation (see Chap. 4) – peaked at 6.1 ktons per year in 1981 (Dittmar, 2011; 2013). In the year 2010 South Africa was extracting uranium at a rate of 0.6 ktons per year, from which only 0.28 ktons were allocated to domestic supply (OECD/IAEA, 2010; Dittmar, 2011; 2013) the rest being sent to exports. When looking at the uranium reserves, South Africa as of 2010 had extracted 157.4 ktons (Dittmar, 2011; 2013) with 195.2 ktons of conventional reserves still available (OECD/IAEA, 2010).

According to the deployment plan forecasted by the South African government, the extraction rate of uranium of a total installed capacity of 11,400 MW will be of 2.0

ktons per year, which corresponds to a total depletion rate of 1% per year from the 2010 estimation of conventional reserves still available.

This assessment suggests that there is relative security of uranium supply matching the deployment plan of nuclear power in South Africa. However, two factors may be affecting the picture significantly.

First, the declining reserves in other uranium producers doubled by the prospects of expansion of nuclear power in other emerging economies such as China, Brazil and India might stress the worldwide uranium demand. In fact, some are forecasting a global uranium mining supply by 2015 leading to shortages of uranium supply from 2020-2030 (Dittmar, 2011; 2013).

Second, and often a disregarded issue, the declining quality of uranium reserves (lower grade of uranium-bearing ore) has been shown as being one of the most influencing parameters on the investment of production factors for the nuclear energy system (Diaz-Maurin, 2011; Lenzen, 2008; van Leeuwen and Smith, 2005; van Leeuwen, 2006). In particular, a sensitivity analysis on the fossil fuels and labor requirements for the mining unit operation of the nuclear energy system has been shown to increase by about 30% and 140% respectively when considering a low value of uranium ore grade (0.045%, which represents the essential of the reserves in Australia (this study considers an average ore grade of 0.15%, see Chap. 4) that is the largest uranium producer totalizing 25% of the world uranium reserves (Diaz-Maurin, 2011). There is a high variation of the uranium ore grades among the uranium mines and most of the worldwide uranium reserves are in the range of 0.01-0.1% ore grade (Lenzen, 2008) which are 100 to 1000 times poorer than those used today (van Leeuwen, 2006). This makes the problem of uranium quality a very relevant issue when assessing the feasibility of nuclear power.

The importance of the resource quality in the quality of energy sources was demonstrated a long time ago in the case of fossil energy sources (e.g. Hall et al., 1986). Yet, there has been little work done on the influence of the quality of nuclear energy production process due to the decreasing quality of uranium ore (Hall and Powers, 2008). For instance, even the MIT study about the future of the nuclear fuel cycle (Kazimi et al., 2011) – considered as the benchmark study in the field – does not discuss the issue of declining uranium ore quality, while it is discussed in other MIT study about coal (Katzer et al., 2007).

(3) Availability of production factors on the sink side

The third constraint in relation with the feasibility of nuclear power refers to the availability of production factors (energy carriers, labor, power capacity) for the Handling waste unit operation (see Chap. 4). That is, there must be production factors made available by society for dealing with waste generated by the nuclear energy system (output on the sink side).

The feasibility on the sink side can also be assessed by looking at the impact on the environment (e.g. effect of the CO_2 generated by coal-fired power plants, see Chap. 4). In this case the assessment of the feasibility requires building an Environmental Impact Matrix (see Chap. 3). In the case of nuclear power however the problem posed by radioactive waste – in a situation where there is no release of radioactive materials directly in the environment – can be reduced to a problem of investment required to deal with those wastes. For this reason it is necessary to evaluate the *size* of the production factors required for this task.

According to the 2010-2030 deployment plan, South Africa will generate annually the following amounts of wastes by 2030:

- 2.7 ktons of high-level waste (HLW);
- 27 ktons of intermediate-level/low-level waste (ILW-LLW);
- 1,263 ktons of very low-level waste (VLLW).

These wastes will require annually the following amount of production factors:

Table 5.7 Requirements of production factors by the nuclear energy system in South Africa for the handling waste unit operation.

ET-t (PJ-EC)	**ET-m (PJ-EC)**	**HA (Mhr)**	**PCD-t (MW-REU)**	**PCD-m (MW-REU)**
5.2	6.0	0.23	52	190

Source: after Diaz-Maurin and Giampietro, 2013 (see also Chap. 4).

The effect of these requirements of production factors on the energetic metabolism of South Africa are shown in sect. 5.3.3.

5.3.3 Viability assessment against internal constraints

This section provides an assessment of the viability of the 2010-2030 deployment plan of nuclear power in South Africa against internal constraints. Those constraints correspond to the congruence among different compartments of society in relation with their relative requirements of production factors. This is called the 'mosaic effect' across scales (see Chap. 3).

The mosaic effect serves two purposes in this application of the energy protocol to the South African case. First, it makes it possible to assess the quality of nuclear power in relation with the current mix of energy sources by looking at the relative requirements of energy carriers and production factors compared to the average requirements from the energy supply sector. Second, it makes it possible to assess the viability of the transition by looking at the investment of production factors required to build the new capacity of nuclear power plants which is very relevant when looking at the large-scale deployment of energy sources – which is the case of the 2010-2030 deployment plan of nuclear power in South Africa.

(1) Quality of nuclear power as an alternative energy source (making and maintenance of flows)

On the basis of the representation of energy flows presented in sect. 5.2, it is possible to discuss the *quality* of nuclear power as an alternative energy source in South Africa by looking at the relative requirements of energy carriers and production factors.

(i) Requirements of energy carriers – The vectorial representation of the concept of EROI of the system can be compared to the Strength of the Exosomatic Hypercycle characterizing the energetic metabolism of the society in the diagnostic analysis (SEH_{diag}). However, at this stage we reach a practical issue. Indeed, as discussed in Chap. 3, it is necessary to keep separated information on different energy carriers (thermal and mechanical). However, in doing so, it is not possible to directly compare the quality of an energy system with the characteristics of the overall energetic metabolism of a society. For instance, the use of nuclear power for generating electricity (mechanical energy) in South Africa shows an EROI equal to: $EROI_{nucl} = [GSEC_{nucl,t} / ET_{nucl,t} ; GSEC_{nucl,m} / ET_{nucl,m}] = [- ; 30]$, which is not directly comparable with the EROI of the whole EM sector – also called the Strength of Exosomatic Hyper-

cycle (SEH), see Chap. 3: SEH_{diag} = [55 ; 223]. For this reason, the effect of the introduction of nuclear power in the energetic metabolism can only be seen at the level of the whole EM sector by comparing the resulting SEH of the diagnostic analysis (current energetic metabolic pattern) with the one of the simulator analysis (2010-2030 deployment scenario of nuclear power):

$$\mathrm{SEH}_{sim} = [\,48\,;\,97\,] \leftrightarrow \mathrm{SEH}_{diag} = [\,55\,;\,223\,] \qquad \text{eq. (5.1)}$$

The above comparison demonstrates that introducing a large-scale deployment of nuclear power in South Africa will affect significantly the overall quality of the energy supply sector in the generation of both mechanical energy and thermal energy due to the investment of production factors required by the nuclear energy system for the making and maintenance of flows – generation of the net supply of electricity (mechanical energy).

(ii) Requirements of production factors – In addition, the quality of nuclear power as an alternative energy source can be assessed by looking at the effect of the scenario on the energetic metabolic pattern of South Africa (tab. 5.8 and 5.9).

Table 5.8 Simulator analysis (making and maintenance of flows) of the 2010-2030 deployment of nuclear power in South Africa (year 2030) – Effect on the energy supply matrix.

EM sector	**Consumption of production factors**					**Supply of Energy Carriers**	
	HA (Mhr)	**ET-t (PJ-EC)**	**ET-m (PJ-EC)**	**PCD-t (MW-REU)**	**PCD-m (MW-REU)**	**NSEC-t (PJ-EC)**	**NSEC-m (PJ-EC)**
EM (n-1)	**500**	**120**	**12**	**2,800**	**380**	**5,600**	**1,100**
PHYSICAL GRADIENTS (n-2)	***430***	***100***	***4.2***	***2,600***	***130***	***4,200***	***800***
Fossil fuels (n-3)	150	37	2.6	370	84	3,600	750
Nuclear (n-3)	44	20	9.4	200	300	-	260
Biofuels (n-3)	270	60	negl.	2,200	negl.	600	3.4
Others (n-3)	negl.	negl.	negl.	negl.	negl.	negl.	5.9
IMPORTS as GER (n-2)	***35***	***0.85***	***0.03***	***9.2***	***0.8***	***1,200***	***7.2***
Fossil fuels (n-3)	35	0.85	0.03	9.2	0.8	1,200	7.2
IMPORTS as EC (n-2)	***negl.***	***negl.***	***negl.***	***negl.***	***negl.***	***260***	***40***
Fossil fuels (n-3)	negl.	negl.	negl.	negl.	negl.	260	negl.
Electricity (n-3)	negl.	negl.	negl.	negl.	negl.	-	40

Note: Effect on whole EM sector and Nuclear power only, other vectors are unchanged.
**: numbers may not add up due to rounding.*

Table 5.9 Simulator analysis (making and maintenance of flows) of the 2010-2030 deployment of nuclear power in South Africa (year 2030) – Effect on the energetic metabolism.

		FLOWS*		**FUNDS***		
CONSUMPTION SIDE		**ET-t (PJ-EC)**	**ET-m (PJ-EC)**	**HA (Ghr)**	**PCD-t (GW-REU)**	**PCD-m (GW-REU)**
WHOLE (n)		**4,400 (-)**	**1,000 (+27%)**	**450 (-)**	**350 (-)**	**400 (-)**
DISSIPATIVE part (n-1)		*4,200 (-0.4%)*	*1,000 (+26%)*	*450 (-)*	*340 (-)*	*400 (-)*
HYPERCYCLE (n-1)		*120 (+16%)*	*12 (+190%)*	*0.50 (+7%)*	*2.8 (+6%)*	*0.38 (+190%)*
LOSSES (n)		**0 (-)**	**120 (+26%)**	**N/A**	**N/A**	**N/A**
EXPORTS (n)		**-1,200 (-)**	**-50 (-)**	**N/A**	**N/A**	**N/A**
SUPPLY SIDE	IMPORTS	1,400 (-)	52 (-)	N/A	N/A	N/A
	EM sector	4,200 (-)	1,100 (+27%)	N/A	N/A	N/A

Note: Only significant changes are shown.
**: numbers may not add up due to rounding.*

By looking at the effect of the simulator analysis on the energetic metabolism of South Africa (tab. 5.9), we see that the production factors invested in the Hypercycle (Energy and Mining sector) would increase significantly – between 6% for PCD-THERMAL and up to 190% for ET-MECHANICAL and PCD-MECHANICAL. That is, the large-scale deployment of nuclear power as foreseen by the South African government would change the characteristics of the overall energy supply sector (HYPERCYCLE) implying changes at the level of the overall energetic metabolic pattern of the country (DISSIPATIVE part). For this reason, it is essential that the choice of a large-scale deployment of nuclear power in South Africa results from a deliberative process of decision-making involving all relevant social actors. Indeed, the analysis of the investment of production factors required for making and maintaining the funds (facilities required by the nuclear energy system) reveals even more significant impacts on the society (at level n) of a choice made over the deployment of a technology (at level n-3).

(2) Availability of production factors for making and maintaining the funds

The scenario of a large-scale deployment of nuclear power proposed by the South African government targeting at generating about 24% of the total electricity supply (see tab. 5.8) would imply the construction of 9,600 MW of new installed capacity between 2010 and 2030. This new installed capacity would consist in about 9 reactors and the other facilities required by the nuclear energy system (see sect. 5.3.1 and also Chap. 4). For this reason, it is necessary to check the viability of this forced transition between the years 2010 and 2030 by looking at the investment of production factors required for making and maintaining this new installed capacity, that will eventually reveal changes on the energetic metabolic pattern of South Africa.

Table 5.10 Simulator analysis (making and maintenance of funds) of the 2010-2030 deployment of nuclear power in South Africa (period 2010-2030) – Effect on the energetic metabolism

	FLOWS*		**FUNDS***		
CONSUMPTION SIDE	**ET-t (PJ-EC)**	**ET-m (PJ-EC)**	**HA (Ghr)**	**PCD-t (GW-REU)**	**PCD-m (GW-REU)**
WHOLE (n)	**4,400** **(-)**	**790** **(-)**	**450** **(-)**	**350** **(-)**	**400** **(-)**
DISSIPATIVE part (n-1)	*4,200* *(-0.3%)*	*790* *(-)*	*450* *(-)*	*340* *(-)*	*400* *(-)*
HYPERCYCLE (n-1)	*120* *(+14%)*	*4* *(-)*	*0.48* *(+4%)*	*2.7* *(+5%)*	*0.13* *(-)*
LOSSES (n)	**0** **(-)**	**92** **(-)**	**N/A**	**N/A**	**N/A**
EXPORTS (n)	**-1,200** **(-)**	**-50** **(-)**	**N/A**	**N/A**	**N/A**

Note: Only significant changes on the consumption side are shown.
**: numbers may not add up due to rounding.*

Tab. 5.10 shows that significant changes are expected on the allocation of production factors – especially thermal energy (fuels) – that will be required in the Hypercycle for the making of the new installed capacity between 2010 and 2030. That is, between 2010 and 2030, 0.3% of the country's consumption of thermal energy – even more when focusing on fuels – will have to be allocated to the EM sector for the making and maintenance of these new facilities. Then, even after that period, a significant investment of production factors will still be required for the maintenance of these facilities that will be added to the existing overhead costs in the energy supply sector.

This implies that South Africa will temporarily have to import or generate more fuels so as to maintain the same amount of thermal energy consumed in the Dissipative compartments, or in alternative reduce some of its functions. As a matter of fact, by adopting such deployment plan of nuclear power, South Africa will see an increase in its energy bill in terms of fossil energy requirements during – and even after – this 2010-2030 period, something that goes against the narrative of breaking the addiction to fossil fuels set by the government (see sect. 5.1.2).

5.3.4 Desirability assessment against benchmarks

The (biophysical) desirability of nuclear power can be assessed by comparing the characteristics of nuclear power with the benchmark values characterizing the energetic metabolism of South Africa. In particular, it is possible to check the *compatibility* of nuclear power with the metabolic pattern of South Africa by looking at the flow/fund ratios: (1) the exosomatic metabolic rate (EMR), in relation with human activity; and (2) the exosomatic metabolic intensity (EMI), in relation with power capacity (see Chap. 3). That way, it becomes possible to directly compare the characteristic of nuclear power (defined at level n-3) with the characteristics of the overall energy supply (EM) sector (defined at level n-1) (tab. 5.11), as well as the two diagnostic and simulator analyses together (tab. 5.12).

Table 5.11 Benchmark characteristics of the significant energy sources used in South Africa (year 2009).

EM sector	**Flow/fund ratios**			
	EMR-t (MJ-EC/hr)	**EMR-m (MJ-EC/hr)**	**EMI-t (MJ-EC/W-REU)**	**EMI-m (MJ-EC/W-REU)**
EM (n-1)	**218**	**9.1**	**39**	**32**
PHYSICAL GRADIENTS (n-2)	***234***	***9.8***	***39***	***32***
Fossil fuels (n-3)	245	18	101	32
Nuclear (n-3)	272	129	101	32
Biofuels (n-3)	226	N/A	27	N/A
Others (n-3)	N/A	N/A	N/A	N/A
IMPORTS as GER (n-2)	***24***	***0.72***	***93***	***32***
Fossil fuels (n-3)	24	0.72	93	32
IMPORTS as EC (n-2)	***N/A***	***N/A***	***N/A***	***N/A***
Fossil fuels (n-3)	N/A	N/A	N/A	N/A
Electricity (n-3)	N/A	N/A	N/A	N/A

Note: Exosomatic metabolic rate (EMR) and exosomatic metabolic intensity (EMI) (for making and maintenance of flows).

The comparison of the flow/fund ratios of nuclear power with the average values at the level of the EM sector reveals that nuclear power demonstrates lower values of EMR and EMI which makes it less desirable than other energy sources. This comparison clearly further illustrates the reason behind the dependence of modern societies to fossil-fuels that shows very low flow/fund ratios compared to alternative energy sources.

Table 5.12 Characteristics of the energy supply sector of South Africa (2010-2030 deployment plan of nuclear power).

EM sector	**Flow/fund ratios**			
	EMR-t (MJ-EC/hr)	**EMR-m (MJ-EC/hr)**	**EMI-t (MJ-EC/W-REU)**	**EMI-m (MJ-EC/W-REU)**
EM (n-1)	**238** **(+9%)**	**24** **(+160%)**	**42** **(+8%)**	**32** **(-)**

Note: Exosomatic metabolic rate (EMR) and exosomatic metabolic intensity (EMI) (for making and maintenance of flows).

As we can see in tab. 5.12, the large-scale deployment of nuclear power in South Africa has significant effects on the characteristics of the energy supply sector, especially in the requirement of electricity per unit of human activity (EMR-m), but also in the requirement of thermal energy per unit of human activity (EMR-t) and per unit of power capacity dissipative (EMI-t). Such differences between the characteristics of the current energy supply (EM) sector (benchmark values) and the resulting characteristics of the same EM sector when considering the 2010-2030 deployment plan makes nuclear power not a desirable energy source as regards biophysical characteristics of energy systems.

5.4 Conclusion

South Africa as an emerging economy is facing rapid changes in its energetic metabolism, especially on the demand side. This implies prospects about large-scale deployment of alternative energy sources, like nuclear power. Yet, the large-scale deployment of a given alternative energy source cannot and should not be considered as *feasible*, *viable*, and *desirable* “by default”. This judgment must result from an assessment of those characteristics describing the *size*, the *quality* and the *compatibility* of the energy source under study (defined at level n-3) in relation with the overall energetic metabolic pattern of society (defined at level n).

In light of the new procedures developed in this thesis, it is possible to assess the feasibility, viability and desirability of the large-scale of nuclear power proposed by the South African government. The simulator analysis reveals that the large-scale deployment of nuclear power of South Africa would imply problems in relation with (1) feasibility – on the supply side (spatial constraints over the location of the new installed capacity, availability and quality of uranium resources), as well as on the sink side (significant requirement of production factors for handling waste); (2) viability – (decreasing SEH, significant requirements of production factors for making the funds); and (3) desirability – (increasing flow/fund ratios).

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Chapter 6
The nuclear essence*

> *We do not have knowledge of a thing until we have grasped its why, that is to say, its cause.*
>
> —Aristotle (*Physics* 194 b17–20)

This chapter explores the "raison d'être" of nuclear power that is a critical piece in the integrated assessment of energy systems and especially in the discussion over their desirability as alternative energy sources. Indeed, by looking at the various *narratives* that have been at play throughout the history of nuclear power it becomes possible to identify key actors and drivers that constitute the *essence* of nuclear power. In particular, after a brief explanation of the importance and role of narratives in science, section 6.1 presents the disturbing concept of 'holon' initially introduced by Arthur Koestler (1968), and further developed by Allen and Giampietro (2006; in press). The concept of 'holon' makes it possible to link a given realization (an instance of a type) to the meaning that the type has within the system in which it is defined. Applied to the field of energetics, the concept of holon is useful to provide – and link together – the thermodynamic *and* the semantic reading of energy systems. Section 6.2 applies the concept of 'holon' to the nuclear energy system to illustrate the non-equivalence of perceptions depending on the observer's role. In this way it becomes possible to understand the existing failure to reach a semantic closure over the desirability of nuclear energy. When adopting this approach, it becomes possible to start a discussion about the "why" of nuclear power which consists in an integrated analysis – multi-scale, multi-dimension and multi-objective – of the semiotic process of nuclear power. To that purpose, section 6.3 provides a necessary overview of the various narratives that have been used throughout the deployment of this energy source. This analysis reveals situations in which different social actors present either contrasting or shared perceptions over this system, as well as the ex-

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[*] Zora Kovacic is co-author of this chapter.

istence of dominant perceptions – hence of dominant actors – over nuclear affairs. This is further analyzed in section 6.4 which provides a discussion based on the use of an analytical tool called "Dominant Narrative Analysis" (DNA) that makes it possible to track dominant narratives and actors, and the subsequent realization of the system throughout the history of nuclear power. This analysis makes it possible to reveal the 'essence' of nuclear power lying at the crosswords of the non-equivalent perceptions of scales, dimensions and values.

6.1 The power of narratives in science

6.1.1 Narratives vs. models

The semiotic process in quantitative science corresponds to the process of validation of formal information through which meaning is assigned to the observed reality. This process is based on the creation of models (formal representations of reality) which are based on the observer's perception. As briefly discussed in Chapter 2, Rosen (1985, 2000) describes the relationship between perception and representation as composed of four steps: (1) identification of the natural system – the perception of a specific state of reality based on the observer's goals and beliefs; (2) the encoding of the relevant qualities of the natural system; (3) the construction of the formal system – the model representing the observed system used to make inferences about the behavior of the observed system; and (4) the decoding of the predictions about the natural system made through the model. If the predictions are consistent with the observed behavior of the natural system, the model is said to reach 'semantic closure'. Semantic closure, in other words, ensures the consistency between perception and representation of a system, which in turn reinforces the narrative upon which the beliefs and goals of the observer are based.

Rosen's (1985, 2000) modeling relation can be used to distinguish between *observer* (or *story-teller*) and *agent*. The observer/story-teller gives meaning and delimits the reality to be studied, acting at the phase of encoding. The agent uses information to affect reality, acting at the phase of decoding. Formal information is created by the observer/story-teller and consumed by the agent. Models and scientific analyses are therefore validated if their meaning is maintained both in the encoding phase – carried out by the observer/story-teller – and in the decoding phase – carried out by the agent. In this case, we can talk about semantic closure achieved in the use of the information.

In the case of nuclear narratives, there is no validation of the formal representations of reality that are associated with the different discourses over nuclear power. In the discourse over costs effectiveness, for instance, the government acts as the observer/story-teller, in describing the emerging technology as a great opportunity for producing cheap electricity (“too cheap to meter”), while reactor vendors and electric utilities act as the agents, experience increasing costs of plant 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. On the other hand, the safety discourse sees public opinion act as the observer/story-teller, encoding nuclear energy in terms of high risk and low benefits, and vendors and utilities act again as the agents, decoding a different reality in which they are facing high costs of complying with new safety measures on already existing plants or on reactor designs. These contrasting perceptions lead to ever growing fears about safety and a distancing of public support of this technology. The discourse on the environment has private companies acting as observer/story-teller, holding that nuclear energy is a clean energy source that can help fight climate change, and public opinion acting as agent, experiencing that nuclear energy implies harmful consequences for humans and the environment because of accidents and the problematic handling of wastes.

Looking at this series of mismatch one can conclude that the main problem lies with the formal information used, which does not help settle the controversies. But would better data, better models and so on be able to solve this debate? As representations reflect the observer's perception of reality (see Chap. 1 and 2) explaining why all models are unavoidably wrong (Box and Draper, 1987), the real issue is whether they are developed within a useful narrative. In other words, the encoding exercise requires a pre-analytical choice of what is to be observed (how and why). The problem does not lie within the complexity of what is observed in the external world, rather complexity lies within the decisions of the story-teller about what to observe (Allen and Giampietro, 2006).

In such a situation, the analysis of ‘narratives’ based on the epistemological studies of theoretical biologists such as T.F.H. Allen and R. Rosen helps putting the semantics (meaning) back to the technical discussion (representation) over the viability and desirability of nuclear power. Indeed, as introduced in Chap. 1, hierarchy theory is “a theory of the observer's role in any formal study of complex systems” (Ahl and Allen, 1996, p. 29). Given that the observer is always there anyway, making his presence explicit helps to clarify the factors that have determined the definition of the system under study (Allen and Giampietro, in press). This is a clear advantage over other theories where the observer is not explicitly considered as affecting the identity of the model.

In the study of complex systems it is important to make a distinction between models and narratives. There are observed systems – e.g. networks in network theory – that can be satisfactory described by models after having clearly defined the scale of the analysis. Whereas when this clear definition is not possible the main methodological objects in hierarchy theory are narratives. Models are internally consistent providing quantitative accuracy. However, they lose stability at higher scale, since they depends on the validity of the assumptions of "ceteris paribus", implied by a fixed scale definition. On the contrary, narratives are very useful for studying how complex systems are becoming in time for their ability of handling changes in the original definitions of type – a situation where models lose their internal validity (Allen and Giampietro, in press). For this purpose, narratives make it possible to bring semantics back to the theory of complex systems (Simon, 1962). A conceptual tool developed in the field of complex systems to handle the perception of events across scales is called 'holon' and it is described below.

6.1.2 The concept of 'holon' and the semantic closure over its autopoiesis

Arthur Koestler (1968) coined the term 'holon' to indicate a standard feature of the perception of complex entities. The concept of holon wants to flag the fuzzy nature of complex entities that are at once an autonomous whole – e.g. a human being – made of subparts – e.g. organs – that at the same time can be seen as substructure of an upper level whole – e.g. a society (see also Allen and Starr, 1982). The concept of holon is fundamental in hierarchy theory as it makes it possible to address the whole/part duality of complex systems (for a review, see Giampietro et al., 2011) requiring the simultaneous use of the internal view and the external view. The reader can recall here the examples given in Chapter 1 about coupled triadic readings obtained when considering the internal view and external view of energetic metabolism. Following the same idea, Salthe (1985) suggests a distinction between "individuals" and "types", whereas Rosen (1985, 2000) proposes another duality between "individual realizations" and "essences" in his general theory of modeling relations. In this distinction we can individuate a key source of complexity in its perception/representation. Individuals are material instances of types. Therefore when dealing with a holon we are dealing with something that is material (the realization) and therefore subject to physical laws (e.g. individuals are subjects to the laws of thermodynamics), but at the same time with something that is just information (the definition of the type). The definition of the type can be subject to axiomatic definitions and rules – semantic and linguistic side – to which thermodynamics no longer applies. Interestingly, this dual view over complex systems was even adopted by those studying how discourses emerge and are controlled saying that beyond the "specificity" (individual realization) of discourses lies their "regularity" (essences) (Foucault, 1970) or, in Aristotelian terms, their "causes".

Coming back to the concept of holon, by relying on the use of narratives it makes it possible to link formal representation (models) and semantic meaning (narrative) of the process of autopoiesis based on the achievement of a semantic closure over the iteration between the recipes (information referring to types) generating metabolic pattern (physical processes compatible with thermodynamic laws) and metabolic pattern generating recipes – as described by Simon (1962). As such, the holon itself is a conceptual tool, not a physical entity, used to describe this iteration (Allen and Giampietro, in press). It acts as the skin of the system (defining what is observed) between the outside and the inside view. That is, by perceiving complex entities as holons we are capable to assign to them a fuzzy identity to which we can refer to both the external view (looking at the interactions between the system and its context regulated by thermodynamic laws) and the internal view (looking at the parts of the system regulated by codes and systems of controls). Adopting Allen and Giampietro's (in press) general example of the process of autopoiesis of a holon associated with the achievement of the semantic closure in a bio-social system, it becomes possible to visualize how this analytical tool can link the formal representation (thermodynamics processing energy/matter flows) and the semantic meaning (the processing information) of a system (see fig. 6.1).

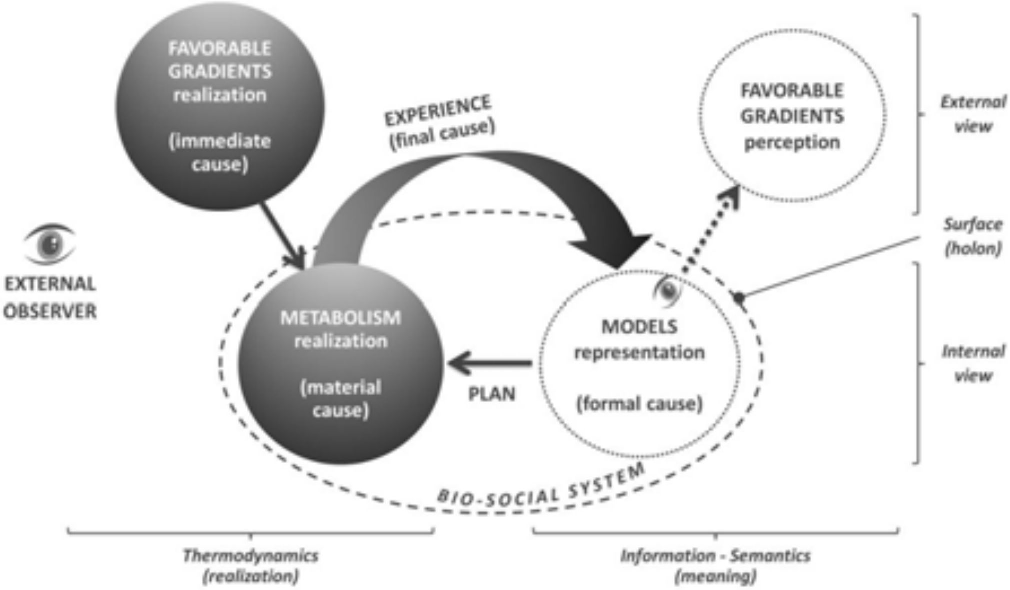

Figure 6.1 General example of the holon of a bio-social system.

Source: adapted from Allen and Giampietro, in press.

As shown in fig. 6.1, the different parts making up the semiotic process of the holon can be named using the four causes proposed by Aristotle in his *Physicae*. As indicated by Allen and Giampietro (in press), the *final* cause gives the holon its meaning that is defined one level higher than the holon itself (at level n+1). In the case of autopoietic system the final cause is the reproduction of the system (the experience obtained with the semantic closure of the semiotic process). The *formal* cause is the planning element inside the holon (at level n-1) – the information used by the socio-economic system in terms of records, blue-print, institutions – that is outside the thermodynamics. The *immediate* cause is the energetic driver of the holon outside the holon (at level n+1) – the material and energy flows associated with the metabolic pattern. The *material* cause is simply the physical realization of the parts and whole of the holon – the structural fund elements making possible the set of thermodynamic transformations stabilizing the metabolic pattern.

The physical laws involved in the holon's thermodynamics are shown on the left side of the figure (immediate cause). Those are rate-dependent (defined at a given time scale) and the holon's metabolism (material cause) looks to the external environment for inputs of matter/energy (favorable gradients). On the other hand, the information processing rules are shown on the right side of the figure (formal cause). Contrary to the thermodynamic laws, these rules are rate-independent and the in-

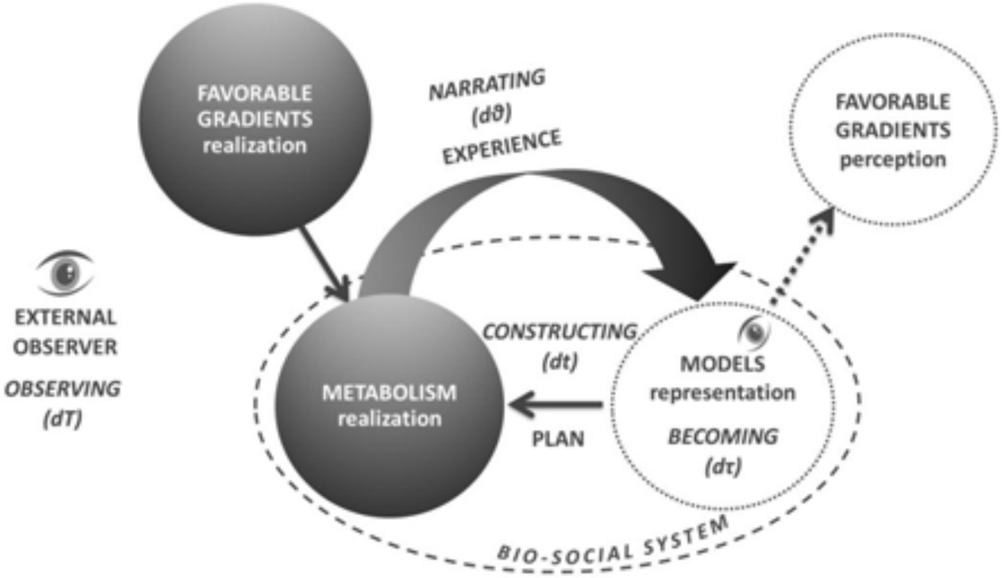

Figure 6.2 General functioning of the semiotic process of the holon of a bio-social system.

Source: adapted from Allen and Giampietro, in press.

formation processor of the holon looks not to the inputs directly, but to an anticipated situation with regard to matter/energy inputs (e.g. favorable gradients running down).

Fig. 6.2 presents the general functioning of the semiotic process of the holon of a bio-social system in the view of Allen and Giampietro (in press).

A plan provides internal constraints to the system (“constructing”) that must be compatible with the availability of the favorable gradients (external constraints, see Chap. 1 and 3). Due to the very characteristics of complex systems, there will be also some emergent properties inside the metabolism that cannot be anticipated (not part of the plan). As a matter of fact, the planned and unplanned changes will be embedded in the outputs generated by the whole metabolism. These outputs 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). Finally, this input will be turned into a change in plan imposed to the metabolism so that the holon will become something else (“becoming”). The whole functioning of the holon can be represented depending on the choice made by observer about what and how to observe such a process (“observing”). In reflexive systems (systems made up by humans) the system is able to observe itself in its own process of reproduction and adjustments throughout the interaction with its context.

Summarizing the functioning of the process of self-reproduction of the holon (operating across different scales and different dimensions of analysis), the whole path determining the semiotic process can be described using the four causes proposed by Aristotle: from n+1 (final) to n-1 (formal), with n+1 (immediate) to make n (the material cause). In linguistic and thermodynamic terms, the sequence iterated in time is:

linguistic–linguistic–thermodynamic–thermodynamic–linguistic.

This conceptualization of the process of autopoiesis of societies is very useful for discussing the “why” of nuclear power for which different narratives explaining its large-scale deployment can be identified and linked together in a set of coherent semantic and formal relations.

6.1.3 Constraints on the time rates in the semiotic process of the holon

As shown in fig. 6.2, the four steps of the semiotic process – observing, constructing, narrating, and becoming – work at different rates – dT, dt, $d\theta$ and $d\tau$ respectively – they correspond to different time scales at which the system can be perceived by the observer. Three types of constraint can be identified on the different time rates involved in the representation of a system that translate key characteristics of the system:

(1) its ‘plasticity’: $dt < d\tau$ – the system must be able to change according to the new plan;

(2) its ‘responsiveness’: $d\theta < dT$ – the system must be able to give a feedback within the time horizon of observation;

(3) its ‘adaptation capability’: $d\tau < d\theta$ – the system must be able to change its identity according to the new narratives (hoping that these narratives are valid).

These time constraints are useful when discussing the quality of energy systems in relation with the energy transitions of societies.

6.2 The semiotic process of the holon of the "nuclear energy system"

6.2.1 The engineering view

The semiotic process of the holon of the "nuclear energy system" corresponding to the engineering view (the conventional perception about nuclear power, see Chap. 2) is shown in fig. 6.3.

In this view, new reactor designs are implemented (process of "constructing", dt = 10 years). Then, the physical realization of the system (material cause) is checked against external constraints (immediate cause, e.g. new failure modes) and provides a feedback (final cause, e.g. higher magnitude of natural events) to the semantic part (process of "narrating", dθ ≈ 8 years, after Diaz-Maurin, 2011). From this experience, the representation of the system (formal cause) evolves (process of "becoming", dτ ≈ 10 years) implying changes in the plan. As this 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). Note that this representation does not include the handling of radioactive wastes.

As we can see from fig. 6.3, the semiotic process of the holon of nuclear power cor-

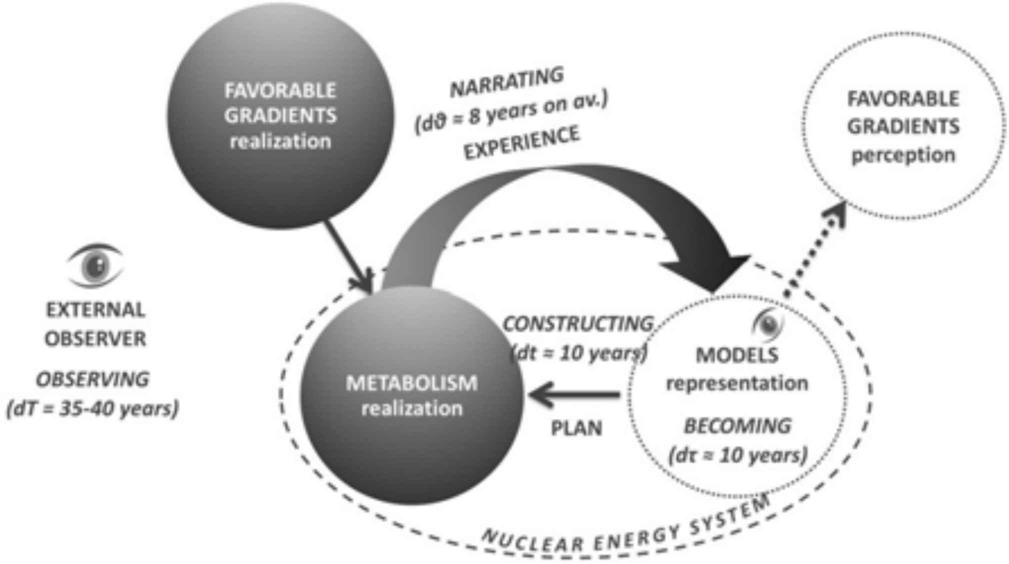

Figure 6.3 The semiotic process of the holon of the nuclear energy system corresponding to the engineering view.

responding to the engineering view seems to be consistent with the constraints over the general functioning of the holon of bio-social systems identified in sect. 6.1.3 (dt ≈ dθ, dτ ≈ dθ and dT > dt). Yet, as extensively discussed in Chap. 2, this view is not satisfactory when dealing with the assessment of nuclear power in relation with the energetic metabolism of societies for the good reason that the "nuclear energy system" cannot be reduced to the attributes of the power plant but requires considering the overall processes of production (see also, Chap. 4). Therefore the main problem of the conventional representation of the semantic closure of the holon shown in fig. 6.3 refers to the fact that it disregards relevant time scales. That is, by adopting the engineering view about nuclear power (dT = 40 years), it is impossible to "see" what happens at larger time scales (e.g. long-term waste management). In fact, in order to address the different steps of the semantic closure it is necessary to adopt different scientific disciplines (Allen and Giampietro, in press). In the case of nuclear power, reactor engineering focuses on the process of "constructing", letting aside the aspects related to the meaning of the system ("narrating" and "becoming").

As a matter of fact the engineering view about nuclear power ignores relevant parts of the meaning-representation complex. For this reason it should not be used to discuss the desirability of this technology at the level of the society. In fact, when dealing with nuclear power in relation to energy transitions it is crucial to shift from an engineering view to a societal metabolism view. This shift is made possible by looking at the system from the discipline of 'complex energetics' (see Chap. 1).

6.2.2 The societal metabolism view

As developed in Chap. 2, nuclear power can also be perceived at the societal level. Indeed, the societal perception of the nuclear energy system corresponds to the view required to discuss the desirability of nuclear power in relation with the energy transition of societies. In this view the semiotic process of the holon corresponding to the societal metabolism view implies some changes in the time rates involved in the nuclear energy system (see fig. 6.4) compared to the engineering view.

As we can see from fig. 6.4, the holon of the nuclear energy system required for discussing the desirability of nuclear power in relation with energy transition at societal level clashes against the constraints over the time rates identified in sect. 6.1.3.

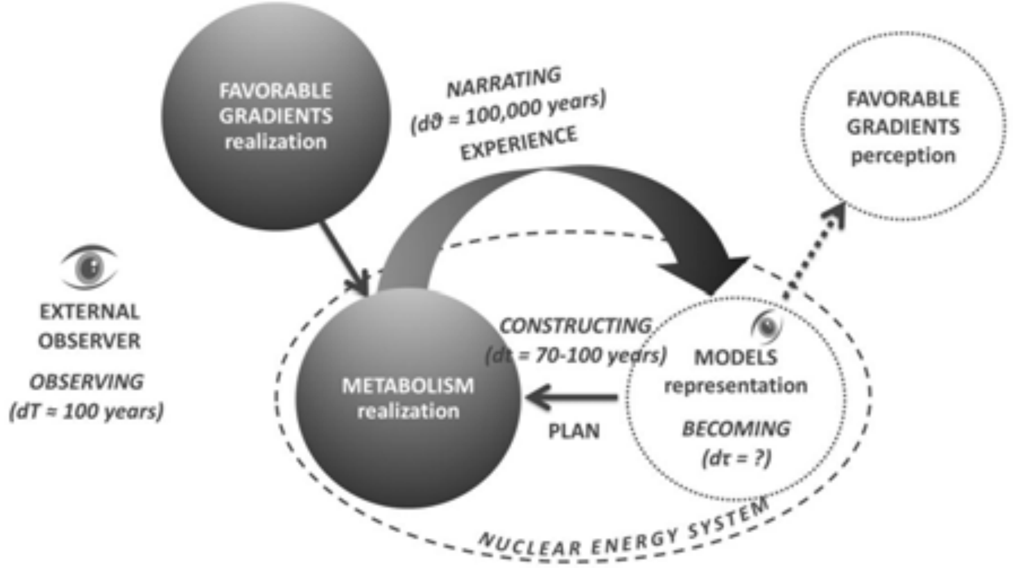

Figure 6.4 The semiotic process of the holon of the nuclear energy system corresponding to the societal metabolism view.

First, the time horizon of analysis required when adopting the societal metabolism view is longer than the one required by the engineering view (dT of about 100 years) as it corresponds to the average time of an energy transition (e.g. Smil, 2010a) – a large scale shift to a different mix of Primary Energy Sources. Yet, this shift in the time horizon required for the formal cause exceeds by far the capability of human societies to organize themselves around such long time periods. This impossibility is mainly due to the unavoidable expiration date of available information about the characteristics of local processes over such a period as well as the inescapable limit set by the life expectation of human beings. In fact, there is a systemic incompatibility in industrial societies between the desired material cause – defined at time rate *dt*, equal to 70-100 years corresponding to the speed at which the nuclear energy system reproduces itself (see sect. 2.3.1 of Chap. 2) including a transition of the overall nuclear-fuel cycle (Kazimi et al., 2011) – and the capability of the formal cause to become something else – defined at time rate *dτ*. So far this incompatibility between the *required* speed of adjustment and the *actual* speed of adjustment has been resolved by putting pressure on the available immediate cause – avoiding change by doing more of the same. This solution has translated into a boost in the pace of depletion of fossil and mineral resources on the supply side. Even worse has been the effect on the sink side due to the incapacity of the environment to absorb the radioactive waste generated by the nuclear energy system. As we can see, the various possible choices over the "time horizon" of the analysis (dT) reflecting a choice of a narrative (perception endorsed by a legitimized story-teller) affect the resulting definition of the nuclear energy system and – most importantly – the definition and formalization of its characteristics (quality). It should be noted also that due to the evident inability 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 reality that require shorter time horizons. This is the reason why the engineering view about nuclear power often is given consideration over the societal metabolism view (e.g. when reducing the risk to health from nuclear power to the immediate number of fatalities – the so-called "death toll" – in case of reactor accident, see Chap. 2).

Second, when considering the long-term management of radioactive waste, dθ becomes equal to thousands of years, whereas the time of observation dT cannot practically be longer than 100 years (as explained above). As a matter of fact, there is 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 (dθ >> dT). This incompatibility between dθ and dT is the most critical issue over the time rates involved with nuclear power as it affects its 'responsiveness' as an energy source.

Considering this set of constraints it becomes clear that it is impossible to reach a semantic closure about how to perceive, represent, adjust, produce and operate nuclear energy systems due to the incompatibility between its different time scales. That is, there is a systemic incompatibility between the formation of a shared meaning about nuclear systems in the society and the realization of nuclear energy systems in the external world. Those discrepancies in the process of narration–perception–representation about this technology explain the observed systemic controversy about nuclear power as perceptions about the benefits and costs of nuclear power (e.g. risk) are not equivalent (see also Chap. 2).

In such situations where the semantic closure is impossible, it is not possible for a component of an autopoietic system to survive, unless it is artificially sustained by reasons not directly related to its expressed function. That is, if its function (i.e. generating cheap electricity in a safe way) is not perceived as effective by the semiotic process, the realization of such a system should stop as it is evident that the actual process fails to update the plan due to a systemic lack of responsiveness and adaptation capability.

Therefore, given the systemic failure in the semantic closure within the semiotic process of nuclear energy systems, what drives the continuous reproduction of the nuclear power industry? That is, is there any 'meta-narrative' (Lyotard, 1984) about nuclear power that justifies its continued reproduction?

According to Jasanoff (2004), knowledge is the result of the co-production of science and social perceptions which makes it hard to identify a clear direction of causality between the narratives used and the development of a technology. The two processes 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. The complex relationship between science and society changes through time, so that the direction of causality may be reversed at different points in time. In the case of nuclear power, we can observe how experience (e.g. unavoidable reactor accidents, see Chap. 2) affected the development of technology, and technology drives the emergence of new narratives (e.g. "too cheap to meter"). The case of the large-scale deployment of nuclear power in spite of the multiple negative feedbacks received from its experience clearly indicates the existence of such complex relations between narratives and experiences.

So the question now is how can we identify these relationships which acted as a meta-narrative making possible the large-scale deployment of nuclear power over the second half of the twentieth century? In order to discover these drivers (not referring to the narrative of a cheap generation of electric energy in a safe way) we can map the dominant individual narratives that have been used throughout the history of its large-scale deployment.

6.3 Historical analysis of the main narratives about nuclear power

> *Nuclear energy was conceived in secrecy, born in war, and first revealed to the world in horror. No matter how much proponents try to separate the peaceful from the weapons atom, the connection is firmly embedded in the minds of the public.*
>
> —Smith (1988: 62, quoted in Slovic, 2012)

This section provides an historical overview of the large-scale deployment of nuclear power by looking at the main narratives that have been making the history of this technology since the 1950s. The realization of the nuclear energy system can be divided in six phases: (i) a first period of exclusive military applications (1939–1945); (ii) followed by a period of initial optimism over its possible civilian application (1946–1953); (iii) the creation of the worldwide 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 (vi) finally a second period of slow down after the reactor accidents at Fukushima (since 2011). Main social actors involved in this debate have been governments, private electric utilities and reactor vendors, as well as the general public (Rosa and Rice, 2004). However their relative perceptions about nuclear energy were not given equivalent attention, meaning that some narratives got more consideration than others. This was especially evident in the early stages of the military and civilian uses of nuclear energy that was both proposed and supported by governments. Below, I first detail the various perceptions for each one of the above-mentioned phases of the history of nuclear energy.

6.3.1 Period of exclusive military applications (1939–1945)

The first phase extends from 1939 to 1945 corresponding to the use of nuclear fission discovered in the late 1930s (Bohr and Wheeler, 1939) for military purposes during World War II (Einstein and Szilárd, 1939; CNRS, 1939). In the U.S., the nuclear program was therefore almost exclusively oriented towards those military purposes 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 of August 1945 Hiroshima and Nagasaki in Japan. During that period of war, there was a conflict between the goals of the U.S. government that wanted any information about those military applications to remain secret and the goals of nuclear scientists having the desire to share information about their latest research on nuclear fission with the scientific community around the world away from military purposes (Szilárd, 1945; New York Times, 25 May 1946).

6.3.2 Period of initial optimism (1946–1953)

The second phase covers the period from 1946 to 1953. As “nuclear energy was conceived in secrecy, born in war, and first revealed to the world in horror” (Smith, 1988: 62, quoted in Slovic, 2012), the main challenge faced by governments in the aftermaths of WWII was to change collective imaginary about the nuclear bombs dropped on Hiroshima and Nagasaki. Yet nuclear energy was still perceived by governments as being of national interest (Duffy, 2004). In particular, in the U.S. the 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) – without any public consultation. That is, in spite of the memory of the recent atomic bombings in Japan, this period was marked by efforts from the U.S. government for designing and building the first nuclear power plants for civil use. Yet this period of initial optimism over the possible civilian use of nuclear energy rapidly fell short for both political and technical reasons.

First, the government-based program led to a contradictory situation where further deployment of nuclear energy for commercial applications would require private investments, hence forcing the government to release information on the current developments about this technology. So far this program was immune to any challenging narrative from other social actors as information was kept secret under the Government-imposed secrecy. This was enacted in the U.S by a strict control for the dissemination of restricted data under the first Atomic Energy Act of 1946 – which marked the official end of the Manhattan Project. The resulting consensus over the use of nuclear energy for civilian applications was therefore possible because only the supporters of such program – nuclear scientists and some politicians – were aware of its existence thus involved in consequent political action – involuntarily in the case of nuclear scientists. The deployment of nuclear energy for civilian purposes was therefore forcing the government to consider other perceptions of other potential story-tellers (proposing different narratives) implying a possible criticism.

Second, from the words of Hyman G. Rickover, a former admiral of the US Navy in charge of supervising the development of the Shippingport Atomic Power Station in Pennsylvania, the world's first commercial nuclear reactor used for generating electricity, there was a crucial difference between “paper reactors” and “real reactors”. Indeed, he later declared in his testimony before the U.S. Congress on 5 June 1953 that:

> *An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose. (7) Very little development will be required. It will use off-the-shelf components. (8) The reactor is*

> *in the study phase. It is not being built now. […] On the other hand a practical reactor can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It requires an immense amount of development on apparently trivial items. (4) It is very expensive. (5) It takes a long time to build because of its engineering development problems. (6) It is large. (7) It is heavy. (8) It is complicated. […] The tools of the academic designer are a piece of paper and a pencil with an eraser. If a mistake is made, it can always be erased and changed. If the practical-reactor designer errs, he wears the mistake around his neck; it cannot be erased. Everyone sees it. […] The academic-reactor designer is a dilettante. He has not had to assume any real responsibility in connection with his projects. He is free to luxuriate in elegant ideas, the practical shortcomings of which can be relegated to the category of "mere technical details." The practical-reactor designer must live with these same technical details. Although recalcitrant and awkward, they must be solved and cannot be put off until tomorrow. Their solution requires manpower, time and money.*
>
> —AEC (1970: 1702)

These two kinds of political and technical difficulties thus explain the lack of investor’s interest whose perception was dominated by an uncertain return on investment of nuclear plants doubled by its certain long time span that made nuclear plants unattractive (Duffy, 2004). In such context, the creation of a civilian nuclear industry was not possible without the government financial support.

6.3.3 Creation of the worldwide nuclear industry (1954–1974)

The third phase goes from 1954 to 1974. The first half of this period was characterized by an “all-out support” dominated by the political dimension until the early 1965, when the actual large-scale deployment of nuclear power started in the U.S. and concerns over environmental and safety aspects arose which gave birth to the first anti-nuclear movement in the World. This period ended with economic concerns over the costs of nuclear power in the aftermaths of the first oil crisis of 1973. This phase is the first one to involve social actors as legitimate proposers of alternative narratives other than the nuclear scientists and politicians who were having strict control over nuclear affairs so far. For this reason, this phase was marked by debates and controversies.

As the early stages of the large-scale deployment of nuclear energy for civilian application was facing political and technical challenges, the government had no choice but to bring this debate to the public place. In such context, some debates regarded the tension between the use of “atoms for war” and “atoms for peace” (Gamson and Modigliani, 1989) epitomized by U.S. President Eisenhower's 1953 speech to the United Nations. Indeed, from the very beginning the debate over nuclear energy was characterized by the dichotomy between faith in progress through technological innovation and the unexpected consequences of technology turning on its creator, as epitomized by Frankenstein's monster. However, at that stage the focus as regard to nuclear energy was still on government and military affairs so that the debate was characterized by a dominant political dimension. As a matter of facts very few actors were so far involved in the debate by the time. In the U.S., the government clearly played an important role both as promoter of the new technology and as regulator (Rosa and Rice, 2004) – something which later was a matter of extreme concern among the general opinion.

To further encourage private companies to invest in nuclear power, the U.S. approved in 1954 an amendment to the Atomic Energy Act of 1946 making it possible to effectively create a civilian nuclear industry. This law was implementing an “all-out support” deployment plan consisting in subsidies and other financial incentives given to private companies along with the necessary technical information that were so far restricted to government use. Consequently, this plan was accompanied by great enthusiasm by private companies. However, in doing so, they were collapsing their own goals in relation with this new technology into the societal perception over the idea of progress (the difference between the “engineering view” and the “societal metabolism view” about nuclear power is discussed in Chap. 2 and in sect. 6.2 of this chapter). This was epitomized in 1954 by Lewis L. Strauss, a former businessman who was recently appointed as Chairman of the United States Atomic Energy Commission[29], in a speech to the National Association of Science Writers:

> *Our children will enjoy in their homes electrical energy too cheap to meter [...] will travel effortlessly over the seas and under them and through the air with a minimum of danger and at great speeds, and will experience a lifespan far*

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[29] The US Atomic Energy Commission is the forerunner of the US Nuclear Regulatory Commission (NRC) and the US Department of Energy nuclear program.

> *longer than ours, as disease yields and man comes to understand what causes him to age.*
>
> —Lewis L. Strauss (1954)

Nuclear power – seen as based on the use of breeder reactors – was even considered as a possible substitute to fossil fuels making possible human societies to live in a "post-scarcity" world emanating from scientists well aware of the scarcity of fossil and mineral resources (e.g. Hubbert, 1956). The irreversible nuclear power illusion was in motion with some even anticipating a "nuclear revolution" (Time Magazine, 6 February 1956).

Under the Atomic Energy Act of 1954, reactor vendors were being created and electric utilities were able to enter the market on "turnkey" contract bases. That is they would be given completed nuclear plants with no additional cost other than switching on the reactor (Rosa and Rice, 2004). Although largely advantageous for the first reactors receiving such financial support, private companies however were still reluctant to make a full-scale commitment to nuclear power (Duffy, 2004). Indeed, as the technology was still new and largely untested, private companies did not have sufficient data about the real costs of building reactors. Moreover, the potential damages from an accident were also unknown so that utilities were concerned about their possible liability in case of a reactor accident. For these reasons, the promises set forth by the government-based deployment plan were struggling to become a reality.

Once again, in its willingness to create a nuclear industry, the U.S. government passed a federal law in 1957 called "Price-Anderson Act" consisting of a no-fault insurance system setting an upper-bound limit to the liability of utilities in case of reactor accident – this Act originally intended to be temporary and expiring in 1967 is still in use today. At this point in time, with a government-funded deployment plan based on subsidies and liability limits, all concerns encountered by private investors were apparently lifted. However, the so-called "nuclear revolution" was still not around the corner. Although orders of new reactors slowly increased in the late 1950s, private investment in nuclear power remained at low levels until the mid-1960s. This was due to two antagonist factors. First, private investors wanted to make sure that generation and distribution of power would remain a private business away from public corporations, thus encouraging them to invest in reactors in place of the government. But at the same time nuclear power was still not economically viable preventing them from investing massively. Given that lock-in situation, the large-scale deployment of nuclear power seemed to be doomed to fail and the nuclear industry to remain a wishful thinking, until a “miracle” happened.

As nicely described by Bupp and Derian (1978) – see also Duffy, 2004 – in their critical appraisal of the history of nuclear power, 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). By making this “tour de force” the two private investors were sending a clear message to their competitors: nuclear power had become a viable alternative for generating electricity. The last deadlock preventing the creation of the nuclear industry had just broken. The U.S. government and private companies were now having a shared perception over the future of nuclear power which opened the path to a period of rapid expansion of this technology throughout the country often referred to as “great bandwagon market” (Bupp and Derian, 1978; Duffy, 2004). In fact, between 1963 and 1967, American utilities ordered 70 reactors, with about 80% of these orders being placed in 1966 and 1967.

When looking back at the history of nuclear power, one can see how the word “miracle” really is adequate to describe the making of this industry. Indeed, it was later found that the two private companies had lost a considerable amount of money in building the Oyster Creek plant, which had been a ‘‘loss leader’’ designed to persuade utilities of the viability of reactor technology (Bupp and Derian, 1978; Duffy, 2004). This strategy eventually worked as private companies started to massively invest in nuclear reactors that were still *not* an economically viable technology. The Oyster Creek plant made nuclear power *perceived* as economically competitive from other private companies, making such a *belief* the origin of the “creation” of the nuclear industry.

During all this period of “great bandwagon market” the public opinion was still virtually absent from the discussions and decisions over nuclear energy, as energy policies were seen as the topic of experts and of a very limited number of politicians (Holmberg and Hedberg, 2010). As a result of this choice from the government of not involving the general public in the debate about nuclear energy, a situation of distrust and misinformation was created leading to the systemic controversy of nuclear power that has never been resolved since then. Indeed, as explained in Chap. 2, the distrust in the institutions in charge of the governance of a technology and the absence of sufficient information received about the same technology are the two main drivers of the *perception* of risks. This created the pre-conditions for the raising public concerns about nuclear power worsen by an economic context of energy crisis. In fact, the public opinion started to express concerns about nuclear affairs by the mid-1960s as nuclear reactors started to being built all around the country without a prior involvement from the public (Duffy, 2004). Those concerns emanating from an issue of governance were rapidly influenced by the birth of environmental and conservationist movements. These movements were illustrated by the publication of Rachel Carson's Silent Spring in 1962 and culminated with the organization of the first Earth Day in 1970, although environmental concerns were not yet directly linked to nuclear affairs yet. The discourse associated with this new movement argued for the development of alternative energy sources, such as wind power, solar power and the like, seen as less harmful to the environment. This environmentalist vision about energy was later epitomized by the proposal of a “soft energy path” (Lovins, 1977) in which large-scale energy developments, especially those relying on nuclear power, were rejected (Krech et al., 2004). Apart from the environmental protection, there were also concerns about nuclear safety and the impacts of radiation on human health (Duffy, 2004). However, those public concerns over environmental and safety aspects remained ignored by the government and private investors as the first oil crisis was pointing.

The 1973 first oil crisis revived economic concerns over the competitiveness of nuclear power plants. At that time, investors did realize that the promises about nuclear power did not match the actual costs of building a reactor. The oil crisis led therefore to a contradictory situation as regard to the desirability and viability of nuclear power. On the one hand, the oil crisis made some to think that electricity – hence nuclear power – was the only alternative to oil (Yang, 2009). Indeed following the oil price spike of 1973, due to the oil embargo imposed by the Organization of Petroleum Exporting Countries (OPEC), a new discourse came into the debate by introducing the issue of energy security, that is, the need to develop sufficient domestic supply from energy sources to meet increasing energy demand. Support to nuclear energy thus shifted from the pursuit of progress to the design of a practical strategy in order to cope with the changing global situation in times of the Cold War. On the other hand, the spike in oil prices convinced many that nuclear power was not a competitive energy source due to its dependence on oil and that, as such, it was not improving the situation as regard to imports of fossil fuels (Bupp and Derian, 1978; for an illustration of this problem to the case of South Africa, see Chap. 5). Although first ignored by those favoring nuclear energy, these concerns were observed in practice through the wave of cancellations of new nuclear reactors that started as soon as 1974 in the U.S. and that was sustained until the early 2000s (see also Chap. 2). That is, contrary to popular belief, the end of the first era of nuclear energy did not happen as a consequence of the first reactor accident at Three Mile Island in 1979 but, *before*, as a consequence of the oil crisis of 1973. That is, although orders of nuclear reactors were sustained until a year after the oil embargo – when investors were still thinking that the economy would rely more on electricity after the oil crisis (Yang, 2009) – they rapidly fell after 1974 (see fig. 2.1 of Chap. 2).

Therefore, the period of fast creation of the nuclear industry ended with harsh debates over the economic viability of nuclear power (Bupp and Derian, 1978; Duffy, 2004). In fact, given the importance of the stakes involved with nuclear energy at that time and the consequences of stopping the deployment program of nuclear energy in case nuclear power would be finally shown as not being economically competitive, a controversy rapidly emerged about the “true” costs of nuclear power. With no surprise, nuclear power became a hot topic in the scientific debate of the 1970s among energy analysts as far as the use of linear input-output analysis in energy accounting (e.g. Chapman, 1975; Leach, 1975; see also Chap. 1).

6.3.4 Halt in nuclear plants construction (1975–2001)

The fourth phase covers the period from 1975 to 2001 which was marked by a sustained halt in the deployment of nuclear power worldwide and the first reactor accidents.

As seen in the previous phase, the post-oil crisis era of the mid-1970s the nuclear optimism came to a halt. The promised economic benefits failed to materialize and the newly formed nuclear industry stopped investing in the technology. A wave of cancellations of orders of new reactors started (Bodansky, 2004). No new nuclear plants were commissioned or being built. The expected reduction in the cost of building reactors never happened (Bupp and Derian, 1978; Grubler, 2010), which made nuclear power to be seen as affected by a systemic lack of economic competitiveness (Duffy, 2004; Bradford, 2012; 2013; for a biophysical explanation of this lack of economic competitiveness, see Chap. 4), which resulted in a sustained halt until the end of the 1990s. The “belief” in the promises of nuclear energy as a substitute to oil had dissolved (Bupp and Derian, 1978; Yang, 2009; Smil, 2010b). Yet, to worsen the situation, concerns over the risks involved by commercial nuclear reactors were rising.

Concerns over nuclear safety started with the large-scale deployment of nuclear power in the U.S. That is, even if there was no previous experience of a major accident of a commercial reactor, nuclear power was seen as a high risk technology because of the issues of governance involved (see Chap. 2). To address these concerns the government ordered a series of reports on the risk involved by nuclear reactors. The main message resulting from those reports – epitomized by the Rasmussen Report from the MIT – was that risk can be managed by the introduction of the formal discipline of probabilistic risk assessment (PRA) in the field of nuclear safety design (Rasmussen et al., 1975; Garrick, 2004). The use of quantitative assessment of risk rapidly divided scientists, a debate that lasted throughout the next few decades (for an extended discussion, see Chap. 2). Despite those efforts for mitigating the risks from nuclear power reactors, public opinion started to oppose nuclear power on the basis of growing concerns over health and environmental effects of radiation, although the core reason was related to the issue of governance of this technology. Such attitude was epitomized by the release of the film The China Syndrome in 1979 illustrating the dangers of nuclear radiations and the invisible threat of atomic energy. The film was released on March 16, 1979, 12 days before the Three Mile Island nuclear accident. That is opposition to nuclear power became a growing concern of public policies prior to 1979, before the world ever experienced any commercial reactor accident (e.g. Otway et al., 1978). These fears were confirmed by the Three Mile Island accident of 1979 in the U.S. A similar situation was observed in Europe, although slightly delayed in time due to a later start on the construction of nuclear power plants, where public opinion started to oppose further expansion of nuclear power. As a consequence by the late 1970s no new plants were commissioned, with the exception of France which pursued its state-owned nuclear program. For instance, in Spain, a moratorium over the construction of new nuclear power plants was adopted in 1984. Then the Chernobyl accident of 1986 in Ukraine confirmed the public’s fears about radiation. In 1987 a referendum even led to a ban of nuclear power in Italy since then. Therefore although opinions were not dramatically affected in the direct aftermaths of these accidents (Gamson and Modigliani, 1989) as opposition to nuclear power started before, the two first commercial reactor accidents of Three Mile Island and Chernobyl irreversibly crippled the nuclear industry worldwide.

Given that the dominant dimension as regard to nuclear affairs clearly was towards safety, the nuclear industry attempted to address those concerns claiming that the lessons from those accidents were learned and that new advanced reactors addressing those safety problems would be soon available and even giving hopes for a second nuclear era (Weinberg and Spiewak, 1984; Weinberg et al., 1985; Fosberg and Weinberg, 1990). The underlying problem however, even acknowledged from the risk experts themselves, was that the learning process of such a complex technology implies inherent safety problems (Weinberg, 1994) with unavoidable or "normal" accidents (Perrow, 1984). Those systemic problems of safety explain the chronic controversy over nuclear power since then (see Chap. 2).

Coming back to the problem of costs, the expected decline of reactor costs never happened. On the contrary, in France, one of the very few countries where the deployment of nuclear power was sustained throughout that period, construction and operating costs of nuclear reactors have followed a negative learning curve (Grubler, 2010), confirming the systemic problem of economic competitiveness of nuclear power (see Chap. 4).

As we see, during that period, nuclear power has been at the center of public (and scientific) controversies over the costs and risks of nuclear power. To the extent that some started to speak of a "technological lock-in" as the innovations claimed by the nuclear industry would not be able to solve the systemic problems affecting this technology (Arthur, 1989; Cowan, 1990).

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

The fifth period encompasses the years 2001 to 2011. The turn of the millennium sees willingness from the U.S. 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 – aiming at limiting the dependence to 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 as a reinforcing argument claiming that nuclear power plants can help reduce CO2 emissions and alleviate global warming. Indeed, nuclear power has been widely described as a "low-carbon" or even "carbon-free" and "renewable" energy source in some cases (e.g. Deutch et al., 2003; Deutch and Moniz, 2006; WNA, 2013), a narrative that goes as far as the *Scientific American* with nuclear power described as "the major source of 'carbon-free' energy today" (Deutch and Moniz, 2006).[30]

As we see the political and environmental dimensions were now dominating the pro-nuclear narrative of the early 2000s. Reactor vendors followed in presenting nuclear power as the most viable alternative in their need to sustain the existing technology. In fact, because of the long return and amount of the investments required to make and maintain the nuclear industry, nuclear power inherently creates a lock-in situation which reactor vendors and utilities were the first to be affected. Indeed, one cannot build an isolated nuclear power plant and use it for just a few months. That is, nuclear power must be large-scale both in space and time or die. Given that to survive nuclear power has historically needed government incentives, some conclude that the nuclear industry would eventually die of old age without having to plan for it (Bradford, 2013).

The inherent large-scale nature of nuclear power creates in return another systemic problem over its governance – in addition the ones over its competitiveness and safety – as the management of such technology is said to require 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). In that sense, the lock in imposed by nuclear power is thus not just technological but also institutional and public accountability is evoked as a way to mitigate this problem. However, although the public opinion in Western countries was slowly showing an increasing (reluctant) acceptance of a "nuclear renaissance" to face the global issues of both peak oil and climate change (Pidgeon et al., 2008), this was not the case of emerging countries where nuclear power was not deployed yet. In fact, by the same mechanisms of perception of risks that were at play in the 1970s in Western countries, public opposition to nuclear energy was rising in emerging countries willing to build their own nuclear industry (e.g. Bidwai, 2011). Indeed, in developing countries,

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[30] This is another example of the confusion between the engineering view and the societal view about nuclear power. Indeed, as extensively discussed in this thesis (see Chap. 2, 3 and 4), the engineering view is useful when assessing technical coefficients at local scale, it must be replaced by the societal metabolism view when assessing the viability and desirability of energy sources in relation with the energetic metabolic pattern of societies. Once we adopt the societal view – which includes all processes required for the making and maintenance of the flows and funds of the energy system – nuclear power clearly demonstrates that it is not a carbon-free technology, even when disregarding the reproduction of funds, i.e. the making and maintenance of the facilities including the nuclear power plant.

where nuclear power has not been deployed yet, there are prospects of such deployment taking the opportunity of their fast growing economies (for an example of the situation in South Africa, see Chap. 5). Unfortunately, lessons of the past deployment in Western countries seem not to have been learned especially in relation to governance issues as nuclear power often is perceived by populations of developing countries as imposed by an oligarchy made of the federal government, local authorities itself and foreign reactor vendors (e.g. Bidwai, 2011; Ramana, 2012; Mathai, 2013).

At that stage, the global situation over nuclear affairs was quite simple. Developing countries like China, India and Brazil, had the required wealth to afford deploying nuclear power but this was accompanied by a strong public opposition, whereas in Western countries, there was a growing public support but the economy was not sufficient enough to deploy nuclear power, especially as the costs of building nuclear reactor continued to increase.

Indeed, in parallel to the prospects of a second nuclear era, new problems came into the picture: the issue of nuclear waste disposal acquired prominence as well as the problem of risks from terrorism after the 9/11 attacks in the U.S. These two new issues were further affecting the viability of nuclear power due to the new facilities required to manage waste and the new safety features required to mitigate terrorist attacks – although it is not clear how to define the risks from terrorism in the case of nuclear power (see Chap. 2). As a matter of facts, for the same reasons as in the 1950s when the government wanted to create a nuclear industry, the U.S. government was forced to provide its (re)deployment plan with a system of financial support. This was made in the form of a new federal Energy Policy Act passed in 2005 that proposed tax incentives and loan guarantees to private investors for building new reactors. However, the old demons of nuclear energy were haunting once again as the promises of a “nuclear renaissance” were showing trouble to convince investors (for more details, see Chap. 2). With a worldwide market of nuclear fission reactors being locked both in Europe and in the U.S., the making of a “nuclear renaissance” was therefore strongly compromised and only emerging economies would remain able to acquire new nuclear reactors. As a matter of fact, this period of hopes of a second era of nuclear power already envisioned as early as the mid-1980s (Weinberg and Spiewak, 1984; Weinberg et al., 1985) turned out to be a mere marketing branding unable to pass economic muster (Bradford, 2010; Nelson, 2010) and definitely got swept under the carpet after the reactor accidents at Fukushima following the Tohoku-Kanto earthquake and follow-up tsunami that occurred on 11 March 2011 in Japan.

6.3.6 Second period of slow down (since 2011)

Finally, the current phase is once again of stall after the reactor accidents at Fukushima in Japan (Schneider and Froggatt, 2012). All the systemic problems of nuclear power are resurfacing at once: reactor vendors have not found a way to lower costs which is worsened by the addition of new safety measures for reactors (e.g. Sovacool, 2011; Shrader-Frechette, 2011; Bradford, 2013); governments have not defined a political and technical strategy to deal with the problem of nuclear waste and to efficiently managed unavoidable accidents (e.g. Takubo, 2011; Perrow; 2011); public opinion is more than ever opposed to further expansion of nuclear power (e.g. Ramana, 2011; Pidgeon and Demski, 2012).

Given those unresolved problems, nuclear power that was seen as eventually not being part of the solution (Ferguson, 2007) started to be seen as actually being part of the problem in energy supply issues after the accidents at Fukushima (Gropp, 2012), something that can be seen as a consequence of the “technological lock-in” evoked earlier. In fact, in the post-Fukushima era, nuclear power appears now to have locked itself in an intricate 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 modes (Nöggerath et al., 2011; Bradford, 2012) –, 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”.

Such a lock-in situation can be explained as being the result of its complex nature (see Chap. 2). Yet, in the past few years and despite these striking systemic problems, the pro-nuclear narrative resurrected around two arguments: “nuclear is the safest form of power” – according to Sir David King, former UK chief scientist (The Guardian, 29 March 2011); and nuclear power is a sustainable technology badly needed by our societies – *“We urge the world not to turn its back on a technology that has so far been much safer than coal, and offers a low-carbon alternative to fossil fuels that is cheaper than most renewables.”* (The Economist, 17 March 2011)

These discourses reflect the emergence of an "addiction to nuclear power" like the one observed by the addiction of modern societies to fossil energy (e.g. Ramos-Martin et al., 2011). Although their drivers may not be of the same nature as nuclear power policies are governed by relations of power between social actors whereas fossil energy has been the engine of the economy since the nineteenth century (Ayres and Warr, 2009; Giampietro et al., 2011; Hall and Klitgaard, 2012).

Two technological innovations hold the hopes of pro-nuclear actors. First, some revive the old dream of using nuclear fusion – which includes a series of different technologies (Stacey, 2010) – for generating electricity that would act as the emergent property of the complex system of nuclear power able to solve its systemic problems of costs and safety all at once – let alone governance issues though. However, as explained in Chap. 4, doubts are that nuclear fusion would even be commercially available at large scale before the end of the century making it simply one further silver bullet (Smil, 2010b).

Others believe that the nuclear energy system can change its very nature as a complex system and become something else, namely a decentralized system based on the use of small modular reactors built by smaller vendor companies – an idea that is not that new (e.g. Gluekler et al., 1985). With this other innovation hopes are put forth of resolving problems of costs, safety, and even of governance. But, again, many doubt that small modular reactors is the innovation that would solve the problems of costs, safety and waste (Makhijani and Boyd, 2010; Glaser et al., in press). On the governance aspect also, one can ask whether a large-scale industry made of large power plants, reactor vendors and utilities could be down-scaled smoothly into a set of small reactors and private companies without dying first, like it is the case of all complex systems in nature. A good example illustrating how "whales evolve slower than fruit flies" (The Economist, 10 March 2012) is the case of major airline companies unable to compete in economic terms with new comers characterized by a smaller and more flexible organization (the so called "low cost companies") entering into an existing market (Rivkin, 2007), let alone the situation where a new market is created with the size of the existing companies (large reactor vendor and utilities) not matching the size of the new products (small reactors).

Prospects over *current* designs – but *future* reactors – are common practice by those favoring nuclear power (e.g. Clery, 2011; Bullis, 2011; see also Cochran et al., 2010) which distorts the assessment over the desirability of nuclear power due to a confusion of non-equivalent time scales (see Box 2.5 of Chap. 2).

In any case, a possible "nuclear resurrection" based on a different set of reactor technologies and related governing rules would imply that the current nuclear energy system must die first, something that does not seem to be part of the plan (e.g. Takubo, 2011). To worsen the situation, it is not clear how societies could afford prospects in several nuclear-related technologies at the same time (e.g. nuclear fusion designs, fast breeder reactors, thorium reactor) given their large R&D costs competing with other energy technologies, worsen by the relative time-scale uncertainties as far as their possible large-scale availability (Magaud et al., 2004; Cochran et al., 2010; Kazimi et al., 2011; Mayumi and Polimeni, 2012).

6.4 Revealing the essence of nuclear power

> When we act, we create our own reality. And while you're studying that reality … we'll act again, creating other new realities, which you can study too, and that's how things will sort out. We're history's actors … and you, all of you, will be left to just study what we do.
>
> —Ron Suskind, Faith, Certainty and the Presidency of George W. Bush,
> N.Y. Times Magazine, Oct. 17, 2004 (quoted in Bradford, 2010).
> This quotation, anonymous in the original article, has since been attributed to Karl Rove, former advisor of Georges W. Bush.

This aim of this section is very simple: taking the message given by Karl Rove seriously, I try here to reconstruct "the reality of nuclear power" by looking at how its large-scale deployment was made possible. In doing so, I provide a dynamic representation of the history of nuclear power consisting in mapping the individual narratives into a 3-dimensional space using a representation based on the double helix of DNA. Following this approach may help identify the knowledge ways through which discourses and perceptions about nuclear power were constructed. Once narratives are linked together they may eventually reveal the *existence* (not a *substantive definition* however) of a line of narratives acting as an attractor. The existence of a 'meta-narrative' – a term originally coined by Lyotard (1984) referring here to the pattern of complex relations between changing and emerging narratives and experiences through time – could shed light over the continuous deployment of nuclear power despite the unresolved systemic problems affecting its desirability.

6.4.1 The analytical tool of "Dominant Narrative Analysis"

Allen and Giampietro (in press) propose a way to deal with the process of changes in time of the dominant narratives used in the semantic closure over the evolution of holons by plotting the course of the holon's meaning and realization as passing along a spiral. I call this process the "Dominant Narrative Analysis" (DNA) as the spiral definition of the holon recalls the schematic representation of the structure of DNA of living systems used in genetics (fig. 6.5).

Fig. 6.5 presents the spiral definition of the semiotic process driving the evolution of a holon which captures the three semiotic steps shown in fig. 6.1. Putting the "becoming" process along an axis the figure makes it possible to keep track of subsequent acts of becoming something else. That is, fig. 6.1 is a flat circular version of fig. 6.5 where changes in the meaning and realization of the system happen around a loop. One loop of the spiral illustrates the semiotic cycle around the holon from the holon's old narrative to its new updated narrative.

The holon starts with a first narrative that represents the anticipated realization of

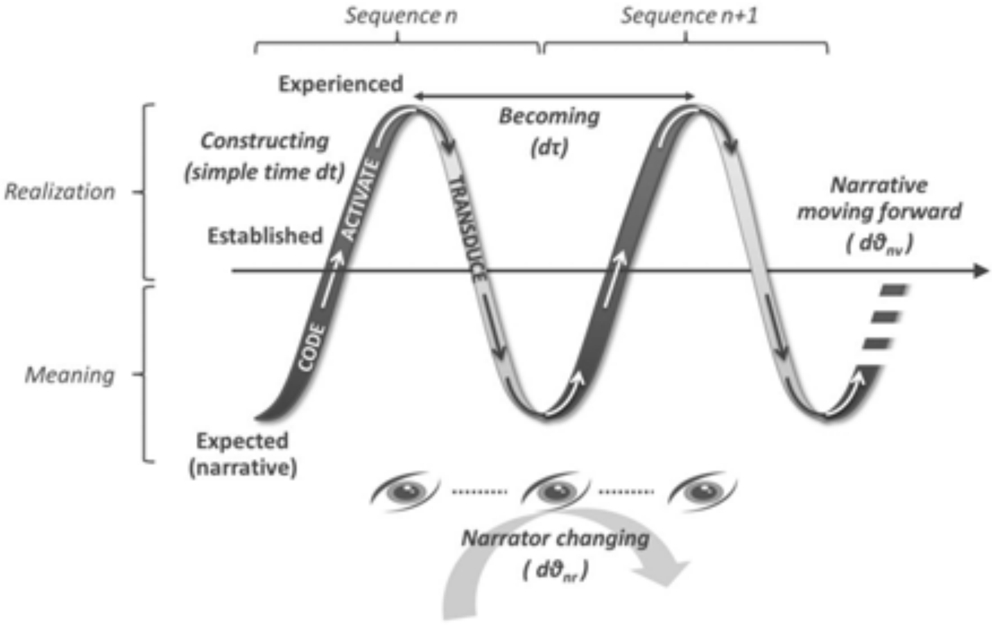


Figure 6.5 The spiral representation of the semiotic process used in the Dominant Narrative Analysis.

Source: after Allen and Giampietro, in press.

the system ("expected" part). For this to happen, the coded narrative is turned into a plan that links meaning to realization ("established" part). Finally, the established realization of the holon because of its action gives back an input to the meaning of the holon ("experienced" part). That is, it is transduced into an updated narrative. The holon is created in the first "code–activate–transduce" sequence that goes "meaning–realization–realization–meaning" following the semiotic process diagram of fig. 6.1. Each time the narrative is updated, it gives the system a new becoming, which 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 its identity is changing at yet another rate $d\theta_{nr}$. The time continuing across a set of becomings is guided by the essence of the holon. The corollary is that the essence of the holon can be defined by the dominant narrative analysis changing at rate $d\theta_{nv}$.

In summary, the Dominant Narrative Analysis consists in checking the sequences of "code–activate–transduce" in time that defines the actual realization ('essence') of the system. Indeed, as explained by Allen and Giampietro (in press), the essence lies behind the realization of the narratives. But any realized system implies the possibility of multiple non-equivalent perceptions and therefore multiple legitimate non-equivalent narratives about it. In this situation it is the relevance of the realization for the story-teller that matters. Therefore, the power relation among potential story-tellers inherently makes some narratives dominant over others. Tracking the essence of a system can be done by studying those dominant narratives that have been able to shape holon's evolution. Yet, as the dominant narrative is always being updated in time, the essence of the system cannot be defined once and for all. That is, at best, only the *existence* of the essence of a system can eventually be detected in the form of a meta-narrative (attractor) illustrating how dominant narratives evolved in time. That is, we cannot measure the essence of a system becoming in time, but rather detect its existence in an indirect way, as done for particles in physics or for extra-solar planets in astronomy. The semantic and formal definitions of the essence itself will always remain out of reach to the observer.

In the next sections I attempt to apply the Dominant Narrative Analysis proposed in this section to the case of the evolution of nuclear power. This exercise will eventually reveal the existence of such an attractor explaining its large-scale deployment over the second half of the twentieth century. Doing so requires first to identify the different main narratives that have existed throughout its history.

6.4.2 Dominant Narrative Analysis of nuclear power

Sect. 6.3 recalls that the actual creation of the nuclear industry in the mid-1960s has been made away from direct public involvement, despite the fact that the first public concerns over environmental and safety aspects were made at the very same period. This illustrates the incompatibility between the *material* cause of the nuclear energy system (the physical realization of the system, see sect. 6.1.2) and the *final* cause (the meaning of the system) when observing nuclear power from the eyes of the general public. This incompatibility shows how the making of the nuclear industry has been the result of asymmetrical power relations with some narratives influencing the definition of the final cause at the expenses of other perceptions. For this reason, the overall history of nuclear energy can be represented in semantic terms through a series of "dominant narratives" succeeding each other since the 1940s.

Using the historical background about nuclear power provided in sect. 6.3 along with the analytical tool presented in the previous section, we can now try to track the dominant actors whose perceptions have been given advantage over others. In doing so, we have to look at the changing expectations (narratives) of the different actors involved throughout the history of nuclear affairs and compare them with the actual realization (plan) of the nuclear energy system (see fig. 6.6). This dominant narrative analysis is performed at global scale for the nuclear energy system, whose very nature is large-scale. A similar analysis could be conducted at country level but this would have to be mapped into a global context. For this reason, the analysis provided below certainly does not provide a full refinement of all possible relevant narratives about nuclear energy that have existed throughout its history. Moreover, any exercise such this one is unavoidably biased by the identity of the story-teller (in this case my-self writing this thesis). The objective here is to check whether from this coarse grain analysis, we can already reveal the essence of the nuclear energy system that can be associated to the set of dominant narratives which have been used to support the expansion of this technology since the 1950s. That is, from the realization of the "holon nuclear energy" observed in the "established" step, one can look at the dominant narratives behind in the "expected" step that have made this realization possible.

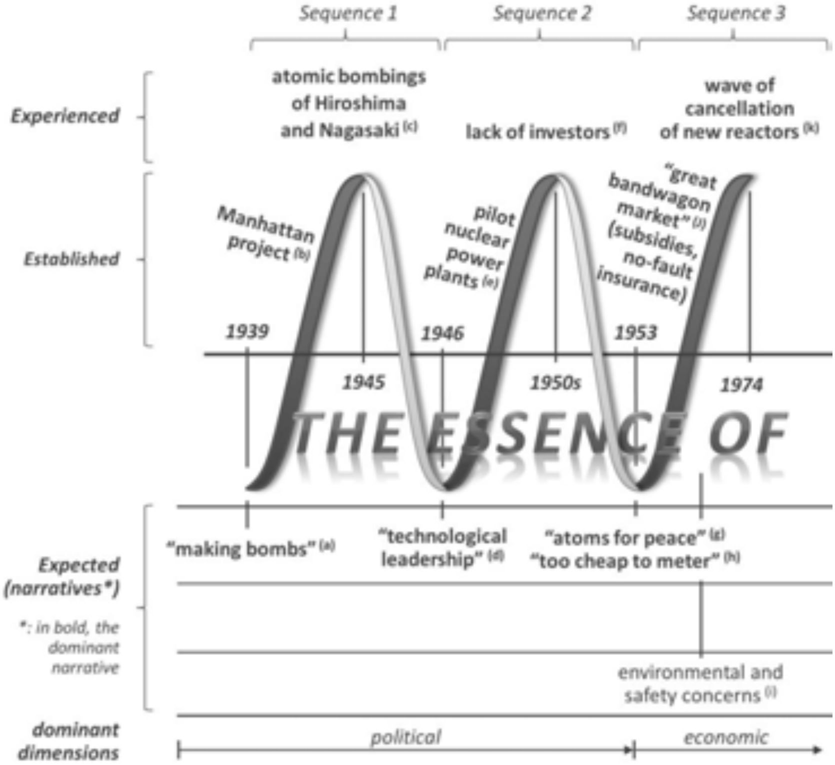
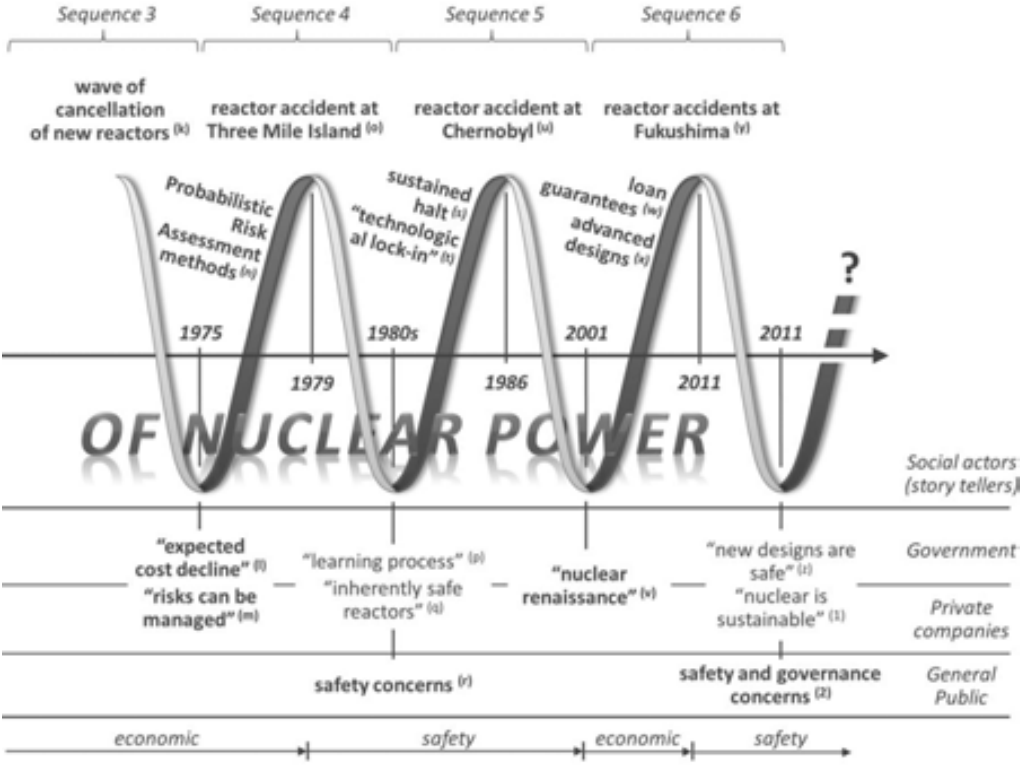


Figure 6.6 Dominant Narrative Analysis of nuclear power.

Source: own elaboration

Notes: (a) "making bombs" (Einstein and Szilárd, 1939); (b) Manhattan project (see http://en.wikipedia.org/wiki/The_Manhattan_Project, accessed 29 August 2013); (c) atomic bombings of Hiroshima and Nagasaki (see http://en.wikipedia.org/wiki/Atomic_bombings_of_Hiroshima_and_Nagasaki, accessed 29 August 2013); (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; Shepard, 2004; Duffy, 2004); (j) "great bandwagon market" (Bupp and Derian, 1978); (k) wave of cancellation of new reactors (Bodansky, 2004; see Chap. 2);



Notes (contd.): (l) "expected cost decline" (Bupp and Derian, 1978); (m) "risks can be managed" (Rasmussen et al., 1975); (n) Probabilistic Risk Assessment methods (see also Chap. 2); (o) reactor accident at Three Mile Island (see http://en.wikipedia.org/wiki/Three_Mile_Island_accident, accessed 29 August 2013); (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_accident, accessed 29 August 2013); (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 August 2013); (y) reactor accidents at Fukushima (Diaz-Maurin, 2011; see also http://en.wikipedia.org/wiki/Fukushima_Daiichi_nuclear_disaster, accessed 29 August 2013); (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. 6.6 presents the sequential evolution of the holon of the nuclear energy system from 1942 to 2011 following the "expected-established-experienced" function described in fig. 6.5. The identity of the nuclear energy system starts in sequence 1 with the use of nuclear energy for military purposes during WWII. During this period, the government narrative was taking control of nuclear affairs over scientists' view (not shown in fig. 6.6), leading to a dominant political dimension until the early 1950s. Since sequence 3, however, the government – the only dominant social actor so far – was forced to focus on the economic dimension of nuclear affairs so as to convince private investors. The subsequent implementation of a large-scale deployment plan made it possible to generate sufficient interest from private companies so as to realize the plan. This created in return a government-private sector collusion which has been maintained until now. That is, each time the meaning part of the holon has been forced to change due to a new input ("experienced" phase), the two social groups have been able to update their own narrative ("transduction" phase, shown in fig. 6.5) and, at the same time, maintain their shared perception about the need of boosting nuclear power.

This was the case for instance of the integration of Probabilistic Risk Assessment methods in reactor safety designs that were claimed as able to mitigate the risks from nuclear power as the first reactor accident of Three Mile Island forced changing the perception of the system – hence its representation. Here it should be noted that the second reactor accident at Chernobyl provided the evidence that the actual implementation of lessons from previous experience (i.e. Three Mile Island accident) is very limited in practice. The realization of the nuclear energy system itself cannot become something else as fast as the meaning and representation of the can be updated. With nuclear power, there is a crucial difference between system's representation (models) and system's realization (experience) – see also Chap. 2.

The existence of a collusion between the two dominant actors – characterized by a shared positive perception over nuclear affairs between government and private sector – 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). That is, nuclear energy guarantees to the government a strong control on the society. The private sector perceives nuclear power, if supported by the government and subsidized with public money, as a powerful stabilizing factor of the status quo. In fact, mega projects supported by public money guarantee a situation of quasi-monopoly to those corporations in the business with sure revenues (i.e. if something bad happens the costs will be paid by tax payers). The importance of such a 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. For instance 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 1980s.

Yet, the survival of nuclear power through the 1980s was made in spite of strongly opposed opinions from other social actors (scientists in the earliest stages and the general public since the 1970s). Indeed, although the view of the general public – characterized by safety concerns (sequence 5) – became seemingly dominant after the Three Mile Island accident, the other driving force behind 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 sustained halt of the 1980s.

When looking at the last sequences of the holon of nuclear power since the 1970s, nuclear power's identity seems entangled into an economic-safety vicious/virtuous circle – depending on the context and the actors' contrasting perceptions – as the dominant dimensions involved. This simply is the illustration of two of its systemic problems of low economic competitiveness and lack of safety (see sect. 6.3). On the one hand, the systemic problem of non-viability of nuclear power is explained by a wrong technology selection (e.g. Weinberg and Spiewak, 1984; Weinberg et al., 1985) driven by lying military purposes leading to issues over its fuel cycle (e.g. Kazimi et al., 2011), when not seen as a delusion (e.g. Proops, 2001; Mayumi and Polimeni, 2012). On the other hand, the systemic problem of safety of nuclear power comes from an incompatibility between model-based claims from the nuclear industry and the reality of perception of risks from the general public driven by distrust and misinformation. Moreover, as explained earlier, those two systemic problems reinforce each other creating that is at the origin of the controversy of nuclear power.

Finally, when looking at what happened in the "transduced" part, the nuclear energy system shows a striking ability to update at fast pace its narratives ("expected" part) depending on the input received in the "experienced" part. That is, to any unexpected and adverse event experienced by the system, there is a consequence and almost immediate expectation as far as what the new realization of the system should be. This culminated in the last sequence experienced by the holon nuclear energy when right after the Fukushima accidents, some were already claiming that new designs are safe (see sect. 6.3.6). As those updated narratives come from the same actors whose perception where already dominating the semiotic process determining the holon, this would eventually also become a dominant narrative making possible to maintain the identity of the system. This can be explained by the fact that, as the history of the system goes, actors' interests and divergences become more pronounced, hence reinforcing their own specific perceptions of the system.

However, as noted above, the inability of the nuclear energy system to integrate the various experiences in the semiotic process due to inherent time constraints implies that it is impossible to use adaptive management with nuclear power, a holon affected by a too large inertia. The only way to solve that problem would then be to increase the size of the administration capability so that it would become big enough to use the feed-back received from experience. As a matter of fact, this is the attempt that has been implemented throughout the expansion of national regulatory agencies as well as of international institutions such as the International Atomic Energy Agency (IAEA). However, this management strategy did not succeed and actually reinforced further the problem of inertia of nuclear power. This fact was clearly illustrated by the ineffective management of the Fukushima accidents in Japan although the country had institutions specially designed for this task (Funabashi and Kitazawa, 2012; Nature Editorial, 16 August 2012). That was also the case of the international institutions in charge of helping countries in the governance of nuclear safety (Brumfiel, 2011a; 2011b).

Moreover, looking at the current pro-nuclear narrative in relation with sustainability, the problem lies in the fact that it would be impossible for the system to generate full experience in relation to this dimension. Indeed, this would require anticipating, (1) on the supply side, the decline of uranium resources – similar to the problem of declining fossil energy resources. This task is difficult when coming to science for governance 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 must be looked over thousands of years. This task is incompatible with the maximum time horizon humans are able to consider in science for governance.

Nuclear power is affected by a systemic problem of governance that prevents it from developing strategies of adaptive management used by living systems to self-organize and survive.

6.5 Conclusion

> *You take the blue pill, the story ends, you wake up in your bed and believe whatever you want to believe. You take the red pill, you stay in wonderland, and I show you how deep the rabbit hole goes.*
>
> —*The Matrix*, 1999

At the beginning of the popular 1999 film *The Matrix*, the protagonist is asked whether he is willing to take the "red pill", capable of showing him the painful truth of reality, or the "blue pill", allowing him to remain within the blissful simulation of reality that the establishment wants him to see. Since then the "red pill" concept has symbolized the possibility of getting a fresh view of something previously perceived in a different way from within a well consolidated framework. In colloquial terms, taking the red pill means accepting the need of thinking outside the box and to challenge the existing perception of the external world. This is what this chapter intended to offer by exploring the *essence* of nuclear power.

Indeed, as shown in this analysis, nuclear power certainly is one of the most controversial technologies and is affected by systemic problems for which no solution is realistically envisioned in any foreseeable future. Yet, the story goes and nuclear energy is still very present in the everyday life of Western countries counting in their energy mix a fleet of operating nuclear power plants. This happens in spite of evident constraints over its desirability after having been at the forefront of one World War and three of the worse industrial disasters ever experienced worldwide. Clearly, no other human-made technology has been as controversial and, at the same time, as largely deployed as nuclear power over the past 60 years. In fact the controversy about nuclear energy can be explained as the result of two factors: on the one hand, the various narratives at stake are based on non-equivalent descriptive domains and incommensurable values; and, on the other hand, the evolution of the holon nuclear power has never reached – and cannot reach – any semantic closure. Therefore the systemic controversy of nuclear power may be treated as a problem of contrasting perceptions and normative values in a world of unequally distributed power among social actors.

For this reason, any sound discussion about the desirability of nuclear power should consider the social dynamics and the co-evolution of narratives and experiences behind the observable realization of the nuclear energy system. Thus some of the most relevant questions about nuclear power today may be formulated as such: What is the *essence* of nuclear power? What actors generate such an essence and what are their motivations? Who wins, who loses with the current identity of the nuclear power-supply system? Could nuclear power ever have existed without these driving forces behind it?

Answering these questions is difficult without using personal values and personal perceptions of this issue. Yet, the dominant narrative analysis of the history of nuclear power performed in this chapter reveals several factors characterizing the existing structure of power relations at stake with nuclear power. First, we see that after a difficult creation of the holon of the nuclear energy system throughout the 1940s and 50s, the system has been mapping onto a set of perceptions shared by a coherent group of actors/story-tellers – government, electric utilities and reactor vendors. These perceptions and narrative made possible its realization at the end the 1960s. Second, since then, the shared perceptions used for realization of the holon remained shared only be the same group of actors/story tellers: the realization of the nuclear energy system has been pursued using similar narratives despite unexpected experienced realization – oil crisis and public concerns followed later by reactor accidents. That is, the nuclear energy system – whose meaning and realization has been supported by the same group of actors/story tellers – has continuously updated the narratives used to justify a positive perception of itself in response to negative feedback coming from the "experienced" step. This ability of performing a creative "transducing" by updating the selection of narratives preserving the original shared perception of the opportunity of developing nuclear energy has made possible the continuous realization of the nuclear power system, hence providing the system its essence. The corollary of this proposition is that, any time the shared perception was lacking (e.g. in the 1940s) or was broken (e.g. in the current post-Fukushima era), the realization of the nuclear energy system has been delayed or even stopped. Again, the simple fact that a *quasi*-continuous realization of the holon "nuclear energy system" has been observed since the 1950s proves the existence of such an essence. However, this essence of nuclear power is strongly related to the existence of a convergence of interests between dominant actors sharing the same positive perception of nuclear power. This perception seems to be based on beliefs not related to thermodynamic or economic reasoning (e.g. Proops, 2001; Bradford, 2010).

In this context, the existence of a "faith-based community" – as opposed to a "reality-based community" (Suskind, 2004) – ruling the nuclear affairs justify the claim that we can talk of the existence of a "nuclear religion" organized around a collection of beliefs, cultural systems, and world views that relate in a normative way humanity to the supernatural, and to spirituality. In fact, religions have narratives, symbols, and sacred histories that are intended to create meaning to life and traditionally explained the origin of life or the Universe. These religious views are based on myths and beliefs turned into a vision of human and societal progress. According to what has been discussed in this thesis we can say that the historical deployment of the nuclear energy technology fits perfectly this pattern. If we accept this fact, then we have to admit that the existence of a "nuclear religion" has non-trivial implications for governance. The members of this religion will perceive the criticism of other social actors not belonging to it as dangerous questioning of the dogmatic foundations and governing rules of this man-made sacred technology. In particular, agnostic views about the imposed identity of this system may be considered as heretic and retaliated accordingly. Unfortunately, there are evidences that such retaliations were widely used in the 1980s against heretic views emanating from scientists on nuclear affairs (Martin, 1986) – let alone the ones used directly on the populations (e.g. Bidwai, 2011). Clearly, proponents of nuclear energy could say that also those that fiercely oppose nuclear energy should be considered as members of an "anti-nuclear religion". However, looking at the iteration of the semiotic process illustrated in Fig. 6.6 we can say that the claim that nuclear energy is capable of providing cheap electricity, in a safe way, preserving the environment, has been proved false several times, whereas the opposite claim has been so far confirmed by experience.

My conclusion is therefore that nuclear power should be seen as a "belief-based" technology (Yang, 2009) for which a "red-pill"-like cure seems to be urgent.

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Conclusion

Contribution to the scientific and public debates

Concluding a thesis of this nature is not easy due to the broad and ambitious objectives and the interdisciplinary approach adopted to this aim. Yet, the two specific objectives:

(1) proposing innovative analytical tools making it possible to handle in quantitative terms and in a systemic way an analysis of the energetics of human societies, and (2) building an integrated view of nuclear power assessing its quality as an alternative energy source in relation to different criteria of performance – seem to have been achieved. That is, the material presented in the previous chapters makes it possible to improve the robustness and transparency of the analysis of the performance of alternative energies and nuclear energy in particular. Clearly as already warned in the introduction, exhaustiveness and quantitative accuracy for this task are a mission impossible.

In addition, the present work may be relevant and useful to increase the quality of the discussion over nuclear energy. In fact, during the writing of this thesis, there has been revived interest from the general public on these two issues. First, due to the reactor accidents of March 2011 at Fukushima the nuclear issue got back on the front burner of public debate. Second, the politically incorrect narrative of peak oil was all of a sudden making the headlines of *Nature* on 26 January 2012 and *Science* on 3 February 2012 bringing back energy-supply issues in the academic debate.

That is to say, as entering in an era of forced transition over the way modern societies deal with energy, it is crucial for science to develop first and foremost a set of procedures able to deal with the complex nature of the societal metabolism in quantitative terms. This scientific input is required to facilitate the informed deliberative process over the desirability and viability of alternative energy sources and of alternative energetic metabolic patterns. By building on previous landmark contributions from co-workers and others, this thesis goes one step further on both the theoretical aspects of the energetics of human societies and on the specific discussion over nuclear power. As such, it will hopefully raise interest both on the scientific arena and on the public place.

Outlook of future research

In addition to the above mentioned objectives, the theoretical part of the present work suggest the existence of prospects for future research in the fields of multi-scale integrated assessment and complex energetics.

First, the revolution of complex energetics exposed in Chapter 1 suggests that the process of "integration by concepts" used to address systemic problems found in energetics – reconciling claims, theories and methods developed in different scientific fields – could be used to cope with similar epistemological problems faced by other fields. In particular, in the field of economics that is once again in a state of crisis since its dominating paradigm of neoclassical economics seems to ignore much of the knowledge developed in other fields dealing with human societies, especially in thermodynamics and theoretical ecology. Past experience of unifications of theories developed in different disciplinary fields in natural science shows that the field of economics could benefit greatly from an integration of its narratives with narratives developed in other scientific fields.

Second, the alternative procedures of complex energetics developed in Chapter 3 suggest that dealing with the energetic transition of human societies requires adopting a larger time scale. In fact, the ability to deal with the dynamic implications of the co-existence of multiple *time* scales appears to be a missing piece in the quantitative integrated assessment of complex systems and in the MuSIASEM approach in particular. One way to address this issue could be to develop a research line consisting in the systemic study of reproduction of *funds* – whose identity is unchanged at the micro and meso time scales but changes at the macro scale imposed by the lifetime of energy converters and other facilities. Therefore, the innovative field of 'powernetics' of human societies should study the dynamic of structural changes determining a new profile of "capacity of energy transformations" among different compartments of society. The operationalization of powernetics in scientific terms would require further theoretical developments in relation with the integration of the larger time scale in the MuSIASEM approach. In doing so, however, this new research line may encounter epistemological problems in relation with the possibility of generating relevant and useful quantitative output, when characterizing societal transitions in the long term. Indeed, even institutions are changing their identity over the time scales involved in energy transitions. As a matter of fact, probably it is impossible to identify any external referent (source of observables) when considering very large time scales so that when dealing with the perception of evolutionary patterns one may reach the limits of using quantitative approaches to sustainability assessment. These problems require further investigation.

Third, the alternative procedures developed in Chapter 4 to characterize the performance of energy-supply systems using biophysical indicators can be used to develop benchmarks in the integrated assessment of alternative energy sources. However, in this thesis I only provided two examples of nuclear energy and fossil energy used to generate electricity. Such a study should be completed by the characterization of other alternative energy sources (e.g. PV, concentrated solar power, wind energy, biofuels, etc.) using the specific grammar proposed in the chapter. In fact, by building a more complete database characterizing the biophysical performance of a significant set of energy sources one could define a set of benchmarks useful for assessing the viability and desirability of “alternative energetic metabolic patterns” (when considering integrated mixes of alternative energy sources), a task crucial in the discussion over energy transitions.

Appendix I

Integrated characterization of the performance of the power-supply systems

This appendix presents the evaluation of all inputs and outputs for the four baseline cases presented in sect. 4.4.2 following the general scheme presented in sect. 4.4.3. In particular, we evaluate (1) the requirements of PES (uranium and coal) necessary to generate the supply of electricity (Input); (2) the production factors necessary for the processes to operate properly including (i) electricity; (ii) power capacity (derived from the fossil-fuels requirements), (iii) human labor; and (iv) other key materials (Inputs); (3) the net supply of electricity generated by the system (Output); and (4) the waste and pollution generated during the process of production (Output). Each type of biophysical requirements is allocated whether it expresses the function of "what the system does" ("direct consumption" in relation to the flows) or "what the system is" ("indirect consumption" in relation to the making and maintenance of the funds).

All the biophysical requirements presented in this section can be found in the Technical Report (Diaz-Maurin, 2012), as well as further explanations on their evaluation. A sensitivity analysis has been performed and can be found in the Technical Report (Diaz-Maurin, 2012), Section 5.5.

I.1 Input of electricity

In the case of nuclear energy, the input of electricity – as well as the fossil-fuels requirements discussed later in this section – have been evaluated using Lenzen's (2008) meta-analysis of about 100 life-cycle assessments (LCA). The data provided only concern the input of electricity in relation to the flows. Indeed, electricity required for the making and maintenance of the funds are not provided in Lenzen (2008). Nevertheless, they can be considered as negligible in comparison to the direct consumption of electricity by the energy system (in particular during the enrichment process).

In the case of fossil energy, the electricity requirements – as well as the fossil-fuels requirements – have been evaluated using the U.S. Department of Energy study (US DOE/NETL, 2010a) that performs an LCA for three recent IGCC designs. For Case 4, the electricity requirements of the CCS technology have been evaluated using an LCA of a pulverized coal power plant which provides details for the capture, compression, transportation and injection processes (Koornneef, 2008).

Tab. I.1 and I.2 present respectively the direct and indirect inputs of electricity for Cases 1 to 4.

Table I.1: Specific direct input of electricity (flows) – Cases 1–4.

Unit Operation	**Nuclear energy**				**Fossil energy**				**Unit**
	Case 1 – LWR power plant		**Case 2 – LWR power plant with reprocessing**		**Case 3 – IGCC power plant**		**Case 4 – IGCC power plant with CCS**		
	mean	**error**	**mean**	**error**	**mean**	**error**	**mean**	**error**	
(1) Mining	0.36	± 0.06	0.30	± 0.05	3.2	-	3.8	-	MWh_{el}/GWh_{el}^{*}
(2) Enriching / Refining	11	± 0.30	9.2	± 0.25	-	-	-	-	MWh_{el}/GWh_{el}^{*}
(3) Generating power	0.94	-	5.9	± 0.10	-	-	-	-	MWh_{el}/GWh_{el}^{*}
(4) Handling waste	21	-	19	-	-	-	120	± 6	MWh_{el}/GWh_{el}^{*}
TOTAL	33	± 0.4	34	± 0.4	3.2	-	120	± 6	MWh_{el}/GWh_{el}^{*}

Source: Diaz-Maurin, 2012.

*Notes: All requirements referring to the reprocessing operation of Case 2 are allocated to the "Handling waste" unit operation as shown in Figure 3; *: Values expressed in relation to the gross supply of electricity.*

Table I.2: Specific indirect input of electricity (funds) – Cases 1–4.

Unit Operation	**Nuclear energy**				**Fossil energy**$^{(a)}$				**Unit**
	Case 1 – LWR power plant		**Case 2 – LWR power plant with reprocessing**		**Case 3 – IGCC power plant**		**Case 4 – IGCC power plant with CCS**		
	mean	**error**	**mean**	**error**	**mean**	**error**	**mean**	**error**	
(1) Mine	not included	-	not included	-	0.32	-	0.32	-	MWh_{el}/GWh_{el}
(2) Enrich. plant / Refinery	not included	-	not included	-	-	-	-	-	MWh_{el}/GWh_{el}
(3) Power plant	not included	-	not included	-	-	-	-	-	MWh_{el}/GWh_{el}
(4) Waste facilities	not included	-	not included	-	N/A	-	-	-	MWh_{el}/GWh_{el}
TOTAL	-	-	-	-	0.32	-	0.32	-	MWh_{el}/GWh_{el}

Source: Diaz-Maurin, 2012.

Notes: (a): Considering a plant lifetime of 30 years (US DOE/NETL, 2010b) and constant Rankine cycle efficiency.

I.2 Net Supply of Electricity (Output)

In tab. I.3, we can evaluate the net supply of electricity generated by the system which can directly be derived from tab. I.1 showing the direct electricity requirements (flows) of the overall system. In strict terms, indirect electricity requirements (electricity consumed by the fund elements associated with the energy flows used by the plant) should not be included in the "electricity input" for the evaluation of the net supply of electricity as those requirements do not deal with the making of the flows. In any case, as shown in tab. I.2, indirect electricity consumption is not significant and can be considered as negligible in comparison with direct consumption.

Table I.3: Net Supply of electricity – Cases 1–4.

Energy Carrier	**Nuclear energy**		**Fossil energy**		**Unit**
	Case 1 – LWR power plant	**Case 2 – LWR power plant with reprocessing**	**Case 3 – IGCC power plant**	**Case 4 – IGCC power plant with CCS**	
	value	**value**	**value**	**value**	
Gross supply of Electricity	9000	9000	4200	3700	GWh_{el}/y
Input of Electricity	300	300	10	440	GWh_{el}/y
Net supply of electricity	8700	8700	4190	3260	GWh_{el}/y

Source: Diaz-Maurin, 2012.

I.3 Requirements of PES (Input)

Requirements of PES correspond to the consumption of uranium or coal (expressed in tonnes) within each system that is necessary to generate the supply of EC (flows). Only direct PES requirements (flows) are provided as they are consumed during the processes of energy transformations in each one of energy systems. For this reason, PES requirements can be referred to as direct material requirements while indirect material requirements corresponding to the other key materials (concrete, steel, copper, etc.) necessary for making and maintaining the facilities are evaluated along with other production factors in sect. I.4. In the case of nuclear energy, requirements of PES have been evaluated using tab. I.1 and I.2. In the case of fossil energy, those requirements derive from tab. I.3 and I.4.

It should be noted that each system also requires inputs of fossil-fuels both for the processes (flows consumed by the power plant in its operation) and the facilities (funds controlling the energy transformations needed for the making and maintenance of the power plant) and that fossil-fuels can either be expressed under the label of PES or EC. However, as mentioned in sect. 4.4.3, we do not perform any aggregation so that fossil-fuels will not be added to electricity (when measured in terms of EC) nor to the requirements of coal and uranium (the two PES of the study). In fact, fossil-fuels – needed during the processes and the making and maintenance of the facilities – correspond to the category of EC that is a useful form of energy that is directly entering into the system just like other production factors (human labor, power capacity, key materials). For this reason, in our study, requirements of fossil-fuels are not included in the evaluation of input of PES but rather are considered as inputs of EC within the evaluation of the production factors (sect. I.4).

Tab. I.4 presents the consumption of Primary Energy Sources (uranium and coal) for all baseline cases (see sect. 4.4.2) per unit of net supply of electricity.

Table I.4: Specific direct PES input (flows) – Cases 1–4.

Primary Energy Source	Nuclear energy				Fossil energy				Unit
	Case 1 – LWR power plant		Case 2 – LWR power plant with reprocessing		Case 3 – IGCC power plant		Case 4 – IGCC power plant with CCS		
	mean	error	mean	error	mean	error	mean	error	
Uranium	21	-	17	-	N/A	-	N/A	-	kgU/GWh$_{el}$
Coal	N/A	-	N/A	-	350	-	470	-	t/GWh$_{el}$

Source: Diaz-Maurin, 2012.

I.4 Requirements of production factors (Inputs)

(i) Fossil-fuels requirements

The fossil-fuels requirements for nuclear energy as well as for fossil energy consider the same references and assumptions as for the electricity requirements presented in sect. I.1. Consistently with the evaluation of inputs of PES in sect. I.3, the consumption of coal in the fossil energy system is not included in the fossil-fuels requirements since it corresponds to the PES of the fossil energy system – like uranium for the nuclear energy system. Instead, the inputs of fossil-fuel evaluated here refer to the consumption in terms of EC – mostly in the form of diesel fuel (OECD/IEA, 2011) needed for the processes (flows) and facilities (funds).

Tab. I.5 and I.6 present respectively the direct and indirect inputs of fossil-fuels for Cases 1 to 4.

Table I.5: Specific direct input of fossil-fuels (flows) – Cases 1–4.

Unit Operation	Nuclear energy				Fossil energy				Unit
	Case 1 – LWR power plant		**Case 2 – LWR power plant with reprocessing**		**Case 3 – IGCC power plant**		**Case 4 – IGCC power plant with CCS**		
	mean	**error**	**mean**	**error**	**mean**	**error**	**mean**	**error**	
(1) Mining	44	± 9.0	37	± 7.5	151	-	205	-	GJ/GWh$_{el}$
(2) Enriching / Refining	5.0	± 5.7	4	± 4.8					GJ/GWh$_{el}$
(3) Generating power	140	± 120	140	± 120	7.0	-	8.1	-	GJ/GWh$_{el}$
(4) Handling waste	66	-	298	± 2.0	N/A	-	not included	-	GJ/GWh$_{el}$
TOTAL	250	± 130	480	± 130	160	-	210	-	GJ/GWh$_{el}$

Source: Diaz-Maurin, 2012.

Table I.6: Specific indirect input of fossil-fuels (funds) – Cases 1–4.

Unit Operation	Nuclear energy(a)				Fossil energy(b)				Unit
	Case 1 – LWR power plant		**Case 2 – LWR power plant with reprocessing**		**Case 3 – IGCC power plant**		**Case 4 – IGCC power plant with CCS**		
	mean	**error**	**mean**	**error**	**mean**	**error**	**mean**	**error**	
(1) Mine	21	-	18	-	3.6E-02	-	4.9E-02	-	GJ/GWh$_{el}$
(2) Enrich. plant / Refinery	11	-	9	-					GJ/GWh$_{el}$
(3) Power plant	58	± 9	58	± 9	2.2	-	2.2	-	GJ/GWh$_{el}$
(4) Waste	16	-	16	-	N/A	-	1.7	-	GJ/GWh

facilities									el
TOTAL	110	± 9	100	± 9	2.3	-	4.0	-	GJ/GWh el

Source: Diaz-Maurin, 2012.

Notes: (a): Considering a plant lifetime of 40 years (Diaz-Maurin, 2012, tab. I.1) and constant Rankine cycle efficiency; (b): Considering a plant lifetime of 30 years (US DOE/NETL, 2010b) and constant Rankine cycle efficiency.

(ii) Power capacity requirements

The power capacity (PC) corresponds to the capability of processing energy carriers in the two energy systems during the production of electricity. It refers to the equivalent capacity of the converters needed to generate the supply of electricity within all unit operations. The power capacity (measured in watts) is evaluated considering the inputs of fossil-fuels necessary during the processes (flows) and for the making of the facilities (funds) by introducing the direct and indirect requirements of EC (fossil-fuels, excluding electricity) as well as the direct and indirect requirements of materials and labor by means of the utilization factor (UF) reflecting the actual utilization of the converters during the overall process of production and thus the labor and materials mobilized. As such, the introduction of the concept of "power capacity" as one of the production factors can be considered as mapping onto the concept of "technical capital" in economics. This concept, therefore, provides another external referent that is independent from the actual assessment of labor and material and energy flows. This additional external referent is very important for assessing the performance of an energy system since it can be used as a proxy for the requirement of fixed investment.

We provide below the formal definition of the direct and indirect PC (for a more refined formalization, see Chap.3):

** Direct power capacity of the converters used for generating power (fund elements for the flow supply)*

$PC_{direct} = (EI_{direct} \times \eta) / (3{,}600 \times UF \times 8{,}760)$

where: (1) EI_{direct} – direct input of EC (fossil-fuels, excluding electricity) required for all unit operations, from tab. I.5; (2) η – conversion efficiency (applied power/energy input) taken from tab. I1–I4; and (3) UF – utilization factor, that is the product of two other factors: UF = CL x OL, where: CL = Capacity Load (fraction of maximum power capacity generated during the period of availability, taken from tab. I1–I4), and OL = Operation Load (fraction of hours of the year of actual use of the converter). While the CL factor has been taken into account in the study (see sect. 4.4.2), the evaluation of the inputs of power capacity refers to the actual use of the converter (OL). This factor reflects the characteristics of the converter, that is, its actual period of availability after considering the periods of unavailability due to maintenance operations (planned) and incidents/accidents (unplanned). In the case of nuclear energy, the OL factor is taken equal to 81% which corresponds to the average availability of all currently operating LWRs in the World (CEA, 2010). In the case of fossil energy, as mentioned in sect. 4.4.2, the availability of IGCC plants is considered equal to the capacity load (US DOE/NETL, 2010b, sect. 2.5). That is, the converter is assumed to be dispatched any time it is available and would be capable of generating maximum capacity when online (US DOE/NETL, 2010b) so that its availability directly provides the overall utilization factor (UF = CL x OL = 100% x 80% = 80%).

** Indirect power capacity for producing and maintaining the converters (fund elements for the making and maintenance of the fund elements)*

$PC_{indirect} = (EI_{indirect} \times \eta) / (3{,}600 \times UF \times 8{,}760)$

where: $EI_{indirect}$ – indirect input of EC (fossil-fuels, excluding electricity) required for power generation, from tab. I.6; while η and UF remain unchanged.

In the above definition of direct PC, we consider that the UF factor depends on the characteristics of the power plant (the main converter of the system), while in strict terms it should refer to the characteristics of each one of the converters necessary during the processes (mine, refining/enrichment plant, etc.) and in the making and maintenance of the facilities (trucks and other diesel machines). Nevertheless, this assumption is not detrimental to the study as converters involved in the Energy sector (process operations) and in the Building & Manufacturing sector (making of facilities) shows more or less the same utilization factor respectively.

It should also be noted that the definition of direct PC does not include the gross power capacity of the power plant itself. Indeed, as discussed earlier, all production factors evaluated in this study must be independent from the capacity of the power plant, including PC. The information referring to the size of the gross power capacity of the power plant is taken into account in the definition of indirect PC that evaluates the requirements (in converters equivalent) necessary to make and maintain the facilities, including the power plant.

Tab. I.7 and I.8 present respectively the direct and indirect input of PC for Cases 1 to 4.

Table I.7: Specific direct input of PC (flows) – Cases 1–4.

Parameter	**Nuclear energy**				**Fossil energy**				**Unit**
	Case 1 – LWR power plant		**Case 2 – LWR power plant with reprocessing**		**Case 3 – IGCC power plant**		**Case 4 – IGCC power plant with CCS**		
	mean	**error**	**mean**	**error**	**mean**	**error**	**mean**	**error**	
$EI_{indirect}$	250	± 130	480	± 130	160	-	210	-	GJ/GWh_{el}
η	33%	-	33%	-	40%	-	34%	-	
CL	79%	-	79%	-	100%	-	100%	-	
OL	81%	-	81%	-	80%	-	80%	-	
UF	64%	-	64%	-	80%	-	80%	-	
$PC_{indirect}$	4.1	± 2.1	7.9	± 2.1	2.6	-	2.8	-	kW/GWh_{el}

Table I.8: Specific indirect input of PC (funds) – Cases 1–4.

Parameter	**Nuclear energy**				**Fossil energy**				**Unit**
	Case 1 – LWR power plant		**Case 2 – LWR power plant with reprocessing**		**Case 3 – IGCC power plant**		**Case 4 – IGCC power plant with CCS**		
	mean	**error**	**mean**	**error**	**mean**	**error**	**mean**	**error**	

$EI_{indirect}$	110	± 9	100	± 9	2	-	4	-	GJ/GWh_{el}
η	33%	-	33%	-	40%	-	34%	-	
CL	79%	-	79%	-	100%	-	100%	-	
OL	81%	-	81%	-	80%	-	80%	-	
UF	64%	-	64%	-	80%	-	80%	-	
$PC_{indirect}$	1.8	± 0.1	1.6	± 0.1	0.04	-	0.05	-	kW/GWh_{el}

(iii) Labor requirements (paid work for both the fund elements and for the flow supply)

Labor requirement is an essential assessment in the analysis of the desirability, feasibility and viability of the metabolic pattern of a society by using the MuSIASEM approach. Indeed, within this approach, independently from local perceptions and specific economic policies decided by the government, a metabolic pattern is viable (in bio-economic terms) only if the primary sectors (agriculture and the energy sector) use a very small fraction of the total amount of human labor (paid work) and the total amount of technical capital (power capacity) used by society (Giampietro et al., 2012). This requirement is essential in order to make possible for the society to invest a large fraction of these resources in expressing transaction activities (service and government) and in final consumption (low labor requirement in the Paid Work sector means more leisure time and dependent population consuming resources, produced by the Paid Work sector) (Giampietro et al., 2011). That is, in order to be able to produce more a modern society must be able to consume more. For this reason, we can say that the metabolic pattern of a modern society is characterized by a high Bio-Economic Pressure (= the need of investing a large fraction of human activity and power capacity into the final consumption activities – Household sector – and transaction activities – Service & Government). As a result of this high level of Bio-Economic Pressure a society has to be able to produce the basic flows consumed (energy, food and material inputs) using only a negligible fraction of human labor. For instance, in the US all the food consumed per capita in a year is produced by 17 hours of work in the Agricultural sector and all the energy consumed per capita in a year is produced by 10 hours of work in the Energy & Mining sector (Giampietro et al., 2011). This translates into an "expected" set of benchmarks describing the performance of the technologies used in the primary sectors. The benchmarks characterizing the high productivity of labor in developed countries – e.g. in the US agricultural sector 700 kg of corn are produced per hour of labor in corn production – are not mandatory thresholds, but we can safely say that if we propose to adopt a technique with a much lower performance – e.g. corn production based on harvesting by hand in which 2 kg of corn are produced per hour of labor – it is very likely that such a technology will result being not economically viable. The same rationale can be applied to the production of energy carriers in society. All modern societies have an Energy & Mining sector capable of guaranteeing a net supply of EC to the rest of society with a productivity of labor in the order of 20 GJ/hour of labor. This benchmark clearly shows that it is important to look at the labor requirements when assessing the quality of an energy system (for more information refer to (Giampietro et al., 2011; 2]).

Labor requirements are difficult to evaluate in the case of nuclear energy given the qualitative and quantitative variations on its production process which makes it difficult to identify the real needs for a given baseline case and at a given time scale. This problem has been acknowledged by the International Atomic Energy Agency (IAEA) saying that “data are scarce on the number of people today with the various skills needed in the nuclear industry” (OECD/IAEA, 2010). In order to overcome this problem, we considered different assumptions (for further detail, see Diaz-Maurin, 2012):

- Labor productivity of the “Mining” unit operation has been evaluated considering the different uranium exporting countries for which both annual employment, production and average grade were provided (OECD/IAEA, 2004).

- R&D efforts for the nuclear power plant design are significant in terms of labor so that they have been included in the “Generating power” unit operation considering the French case of the deployment of generation II reactors (1971–2002) (Bataille and Galley, 1999; CEA, 2009).

- Labor requirements for the dismantling of the power plant are also difficult to evaluate. Indeed, the experience of the first decommissioning around the World has shown high variations in terms of financial costs (Lenzen, 2008) even exceeding in some cases the costs of construction of the facility. The same applies to labor requirements. We considered here an average dismantling cost of 35% of the construction cost that is consistent with Lenzen's (2008) meta-analysis.

- Labor requirements for the "Handling waste" unit operation are evaluated considering the case of France where employment at the ANDRA – the French agency in charge of waste management – makes it possible to isolate labor requirements distributed among waste categories (HLW, ILW and LLW).

- For Case 2, labor requirements for the reprocessing operation are based on the French experience of the La Hague site.

For the fossil energy system, direct labor requirements (to generate flows) for the operation process of the "Generating power" unit operation have been evaluated considering data from the US Census on the fossil-fuel electric power generation at the national level for the year 2002 (U.S. Census Bureau, 2004). As far as the indirect labor requirements (for the making and maintenance of funds), no data have been found in the literature. However, when looking at the much lower specific fossil-fuels requirements of the fossil energy system compared to the nuclear energy system (see tab. I.5 and I.6), we can reasonably consider that they would remain negligible compared to direct labor requirements. Yet, we considered a certain amount of indirect input of labor in the case of fossil energy using the following approach: since there is a direct relation between material requirements and labor requirements when making and maintaining fund elements (facilities) – assuming that the machines used for the construction/dismantling efforts are the same – we can evaluate the indirect labor requirements of the fossil energy system by using the same ratio between indirect material requirements (concrete) and indirect labor requirements of the nuclear energy system (Case 1) and then multiply it by the indirect material requirements of the fossil energy system, which gives us 15h/GWh and 28h/GWh for Cases 3 and 4 respectively.

Last, in order to express the labor requirements in terms of hours (in contrast to "man-year" unit seen in Diaz-Maurin, 2012), 1,800 annual working hours have been considered for both nuclear energy and fossil energy systems which correspond to the average value in the OECD countries (OECD, 2008).

Tab. I.9 and I.10 present respectively the direct and indirect inputs of labor for Cases 1 to 4.

Table I.9: Specific direct input of labor (flows) – Cases 1–4.

Unit Operation	**Nuclear energy**				**Fossil energy**				**Unit**
	Case 1 – LWR power plant		**Case 2 – LWR power plant with reprocessing**		**Case 3 – IGCC power plant**		**Case 4 – IGCC power plant with CCS**		
	mean	**error**	**mean**	**error**	**mean**	**error**	**mean**	**error**	
(1) Mining	367	-	309	-	42	-	57	-	h/GWh_{el}
(2) Enriching / Refining	25	-	21	-					h/GWh_{el}
(3) Generating power	83	-	83	-	23	-	30	-	h/GWh_{el}
(4) Handling waste	2.9	-	2.8	-	N/A	-	not includ cluded	-	h/GWh_{el}
TOTAL	480	-	410	-	65	-	87	-	h/GWh_{el}

Source: *Diaz-Maurin, 2012.*

Table I.10: Specific indirect input of labor (funds) – Cases 1–4.

Unit Operation	**Nuclear energy**$^{(a)}$				**Fossil energy**				**Unit**
	Case 1 – LWR power plant		**Case 2 – LWR power plant with reprocessing**		**Case 3 – IGCC power plant**		**Case 4 – IGCC power plant with CCS**		
	mean	**error**	**mean**	**error**	**mean**	**error**	**mean**	**error**	
(1) Mine	not included	-	not included	-	not included	-	not included	-	h/GWh_{el}
(2) Enrich. plant / Refinery	not included	-	not included	-					h/GWh_{el}
(3) Power plant	163	-	163	-	15	-	28	-	h/GWh_{el}
(4) Waste	not in-	-	not in-	-	N/A	-	not in-	-	h/G

facilities	cluded		cluded				cluded		Wh$_{el}$
TOTAL	160	-	160	-	15	-	28	-	h/GWh$_{el}$

Source: Diaz-Maurin, 2012.

Note: (a): Considering a plant lifetime of 40 years (Diaz-Maurin, 2012, tab. 1) and constant Rankine cycle efficiency.

(iv) Material requirements (for the making and maintenance of the fund elements)

Material requirements correspond here to the key materials necessary to make and maintain the funds. They can be referred to as indirect material requirements while direct material requirements correspond to the input of PES (see sect. I.3). The intent here only is to provide orders of magnitude on the most common materials: (i) concrete, (ii) steel and (iii) copper. In the case of nuclear energy, material requirements have been evaluated using van Leeuwen and Smith's (2005) study for the power plant and Lenzen's (2008) study for the waste facilities. In the case of fossil energy, those requirements have been evaluated using the same reference as for electricity and fossil-fuels requirements (US DOE/NETL, 2010a).

Tab. I.11 presents respectively the indirect input of materials for Cases 1 to 4.

Table I.11: Specific indirect material requirements (funds) – Cases 1–4.

Material	**Nuclear energy**[(a)]				**Fossil energy**[(b)]				**Unit**
	Case 1 – LWR power plant		**Case 2 – LWR power plant with reprocessing**		**Case 3 – IGCC power plant**		**Case 4 – IGCC power plant with CCS**		
	mean	**error**	**mean**	**error**	**mean**	**error**	**mean**	**error**	
Concrete	13	± 0	12	± 0.5	1.2	-	2.2	-	t/GWh$_{el}$
Steel[(c)]	490	± 84	490	± 84	360	-	590	-	kg/GWh$_{el}$
Copper	35	-	31	-	5.6	-	12	-	kg/GWh$_{el}$

Source: Diaz-Maurin, 2012.

Notes: (a): Considering a plant lifetime of 40 years (Diaz-Maurin, 2012, tab. I.1) and constant Rankine cycle efficiency; (b): Considering a plant lifetime of 30 years (US DOE/NETL, 2010b) and constant Rankine cycle efficiency; (c): Including reinforcing steel and structural steel.

I.5 Generation of waste/pollution (Output associated with the flows)

Waste and pollution generated by the two systems correspond to the flows of materials exiting the system as output (along with the Net supply of EC) and that requires handling (waste) and control (pollution). Although there are various kinds of waste and pollution that actually are generated through energy systems, we focus here on the radioactive wastes in the case of nuclear energy and the CO2 emissions in the case of fossil energy. In fact, radioactive waste and CO2 emissions generated during the processes of production of electricity are the direct result of the two systems, while other waste and pollution would come as indirect outputs of the making and maintenance of the facilities. In this way, this study focuses only on direct generation of waste and pollution throughout the overall system.

In the case of nuclear energy, the radioactive wastes come from the various subprocesses of the uranium fuel cycle. As shown in Figures I.1 and I.2, there are three waste categories (HLW, ILW and LLW) depending on the level of radioactivity the waste materials release and that require specific handling efforts (see sect. I.4). In addition, there is a fourth category (VLLW) for which waste materials can be directly disposed without particular effort. Nevertheless, for the purpose of this evaluation of the quantities of waste exiting the system, we cover all four categories. In doing so, we sum up the quantities referring to (1) HLW, ILW and LLW waste entering into the Waste disposal that requires long term management operations; and (2) the VVLW waste exiting the system after the Mining operations and Waste storage.

In the case of fossil energy, the CO2 emissions are coming from the sole combustion of coal inside the power plant. Note that although the CO2 capture rate of the Case 4 is 90%, the final CO2 emissions of the fossil system is not reduced by 90% between Case 3 and Case 4 as the presence of the carbon capture system decreases the overall efficiency of the plant, hence a higher consumption of PES (coal).

By focusing on these outputs generated for each system, it becomes possible to evaluate the inputs of production factors (materials, labor, power capacity) associated with the processes (flows) and facilities (funds) of the “Handling waste / Controlling pollution” unit operation, and thus, to compare the performance of the two systems in relation to this phase.

Tab. I.12 provides the specific waste and pollution outputs for Cases 1 to 4.

Table I.12: Specific waste and pollution outputs – Cases 1–4.

Material	**Nuclear energy**				**Fossil energy**				**Unit**
	Case 1 – LWR power plant		**Case 2 – LWR power plant with reprocessing**		**Case 3 – IGCC power plant**		**Case 4 – IGCC power plant with CCS**		
	mean	**error**	**mean**	**error**	**mean**	**error**	**mean**	**error**	
Radioactive waste	16	-	14	-	N/A	-	N/A	-	t_{VLLW}/GWh_{el}
	340	-	330	-	N/A	-	N/A	-	$kg_{ILW/LLW}/GWh_{el}$
	34	-	31	-	N/A	-	N/A	-	kg_{HLW}/GWh_{el}
CO2 emissions	N/A	-	N/A	-	700	-	110	-	t_{CO2}/GWh_{el}

The evaluation of the CO2 emissions in the case of the fossil energy system brings us to an important point when assessing the quality of energy systems. Indeed, we often find in literature – especially in LCA analyses – evaluations of the CO2-emissions equivalent of the overall process production, so that the quality of different energy systems can be assessed against this criterion. However, in our study, it is not necessary to perform such an aggregation as the consumption of fossil-fuels by the system belongs to a specific analysis along with other production factors. In fact, doing such an aggregation in terms of CO2-emissions equivalent definitely is not an effective analytical approach as it brings the same excessive simplifications of reductionism as the ones observed in energy analysis (see Chap. 1). Indeed, when performing a life cycle assessment of the CO2 emissions of an energy system, it is impossible to avoid mixing two different kinds of emissions: the CO2 emissions generated by the combustion of fossil PES in the power plant (e.g. coal in the case of fossil energy system) and the greenhouse gases (GHG) emissions (including CO2 emissions) coming from the other sub-processes (e.g. consumption of fossil-fuels for the making and maintenance of facilities). This confusion becomes significant when trying to compare the performance of two energy systems that do not consume the same type of PES, especially when comparing fossil-based energy systems (e.g. coal-fired power-supply systems) with mineral-based (e.g. nuclear energy) or renewable-based energy systems. Indeed, such assessments do not provide information on the GHG emissions emanating from every unit operation. On the contrary, our study makes it possible to keep separated information on the waste and pollution (e.g. CO2 emissions) and on the other production factors (e.g. fossil-fuels) related to each power-supply system. In addition, our analytical scheme makes it possible to know the differences between two energy systems for each one of their unit operations.

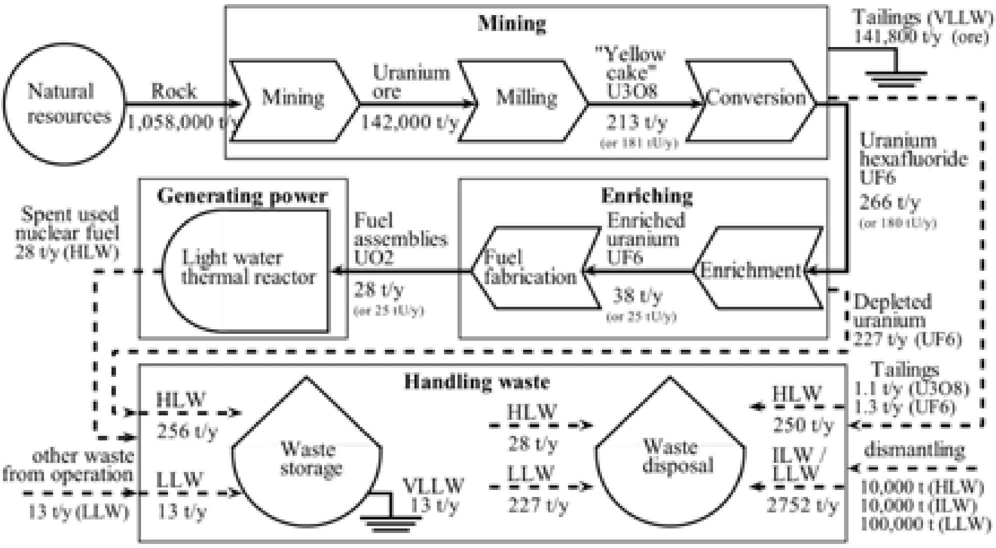

Figure I.1: Mass balance of Case 1 (once-through nuclear fuel cycle).

Source: own elaboration (see Diaz-Maurin, 2012, sect. 4.4).

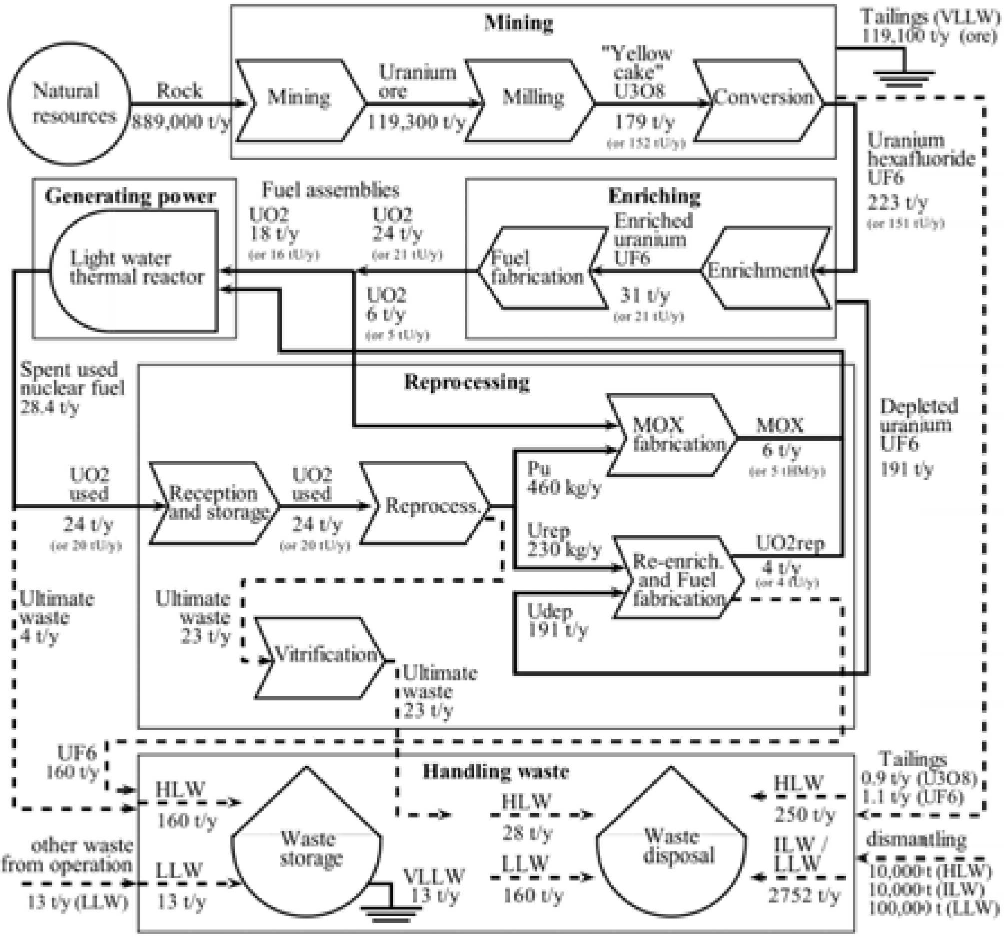

Figure I.2: Mass balance of Case 2 (partly-closed nuclear fuel cycle).

Source: own elaboration (see Diaz-Maurin, 2012, sect. 4.4).

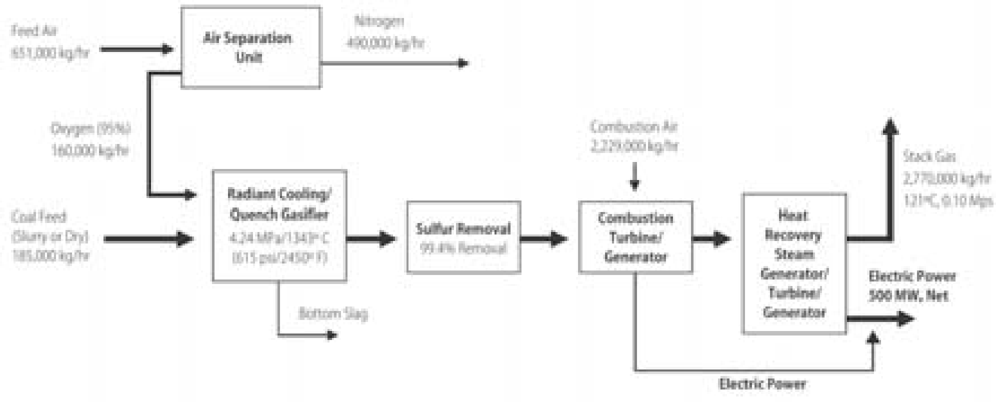

Figure I.3: Example of a 500 MWe IGCC unit with CCS.

Source: Katzer et al., 2007.

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Appendix II

Characterizing the energetic metabolism of South Africa

This appendix provides two sets of information:

(1) the entry points that correspond to the typologies of data used for the case study of South Africa; and

(2) the logical framework of the energy analysis by means of a set of steps (with tables) presenting how the outputs are generated. The logical framework makes it possible to understand the formalization of the analysis and especially how to deal with non-equivalent forms of energy in one integrated analysis – which theoretical aspects are further explained in Chap. 3 and 4.

II.1 Entry points

(1) Energy statistics on imports and local supply

Tab. II.1 presents the energy statistics (excerpts) that have been used to generate the energy analysis in relation to the different energy products from imports or from local supply – expressed in physical units (tonnes, m3, etc.) or in thermal equivalent units (e.g. toe).

Table II.1: Excerpts of energy statistics on imports and local production used for the energy analysis – South Africa, year 2009

PRODUCT CAT	PRODUCT SUB-CAT	INDICATOR	VALUE	UNIT
Coal	Coal and Peat	Production	141,681	ktoe
Crude Oil	-	Production	150	ktoe
Oil Products	-	Production	0	ktoe
Natural Gas	-	Production	851	ktoe
Nuclear	-	Production	3,337	ktoe
Renewables	Hydro	Production	125	ktoe
Renewables	Geothermal, Solar, etc.	Production	64	ktoe

Renewables	Biofuels and Waste	Production	14,429	ktoe
Energy carrier	Electricity	Production	0	ktoe
Energy carrier	Heat	Production	0	ktoe
Coal	Coal and Peat	Imports	1,354	ktoe
Crude Oil	-	Imports	24,234	ktoe
Oil Products	-	Imports	6,298	ktoe
Natural Gas	-	Imports	2,858	ktoe
Nuclear	-	Imports	0	ktoe
Renewables	Hydro	Imports	0	ktoe
Renewables	Geothermal, Solar, etc.	Imports	0	ktoe
Renewables	Biofuels and Waste	Imports	0	ktoe
Energy carrier	Electricity	Imports	1,057	ktoe
Energy carrier	Heat	Imports	0	ktoe
Coal	Coal and Peat	Exports	-45,234	ktoe
Crude Oil	-	Exports	0	ktoe
Oil Products	-	Exports	-2,701	ktoe

Source: OECD/IEA, 2011.

(2) Energy statistics on electricity generation and consumption

Tab. II.2 presents the energy statistics (excerpts) that have been used to generate the energy analysis in relation to the electricity generated per systems as well as the electricity consumption per sectors – expressed in Watt-hour (Wh).

Table II.2: Excerpts of energy statistics on electricity production and consumption used for the energy analysis – South Africa, year 2009.

PRODUCT CAT	PRODUCT SUB-CAT	INDICATOR	VALUE	UNIT
Energy carrier	Electricity	Electric power consumption (kWh)	223,520,000,000	kWh
Energy carrier	Electricity	Electric power transmission and distribution losses (% of output)	10	%
Energy carrier	Electricity	Electric power transmission and distribution losses (kWh)	24,280,000,000	kWh
Energy carrier	Electricity	Electricity production (kWh)	246,815,000,000	kWh
Energy carrier	Electricity	Electricity production from coal sources (% of total)	94	%

Energy carrier	Electricity	Electricity production from coal sources (kWh)	232,196,000,000	kWh
Energy carrier	Electricity	Electricity production from hydroelectric sources (% of total)	1	%
Energy carrier	Electricity	Electricity production from hydroelectric sources (kWh)	1,452,000,000	kWh
Energy carrier	Electricity	Electricity production from natural gas sources (% of total)	0	%
Energy carrier	Electricity	Electricity production from natural gas sources (kWh)	0	kWh
Energy carrier	Electricity	Electricity production from nuclear sources (% of total)	5	%
Energy carrier	Electricity	Electricity production from nuclear sources (kWh)	12,806,000,000	kWh
Energy carrier	Electricity	Electricity production from oil sources (% of total)	0	%
Energy carrier	Electricity	Electricity production from oil sources (kWh)	49,000,000	kWh
Energy carrier	Electricity	Electricity production from oil, gas and coal sources (% of total)	94	%
Energy carrier	Electricity	Electricity production from renewable sources (kWh)	1,764,000,000	kWh
Energy carrier	Electricity	Electricity production from renewable sources, excluding hydroelectric (% of total)	0	%
Energy carrier	Electricity	Electricity production from renewable sources, excluding hydroelectric (kWh)	312,000,000	kWh

Source: World Bank, 2009.

(3) Technical coefficients on energy systems

The energy analysis requires information on the various technical coefficients characterizing the different energy systems (for the most significant energy technologies only) used in each case study, such as:

- net supply of energy carriers,
- average size of plants (unit's power capacity),
- average annual utilization factor (number of hours of use per year; and fraction of the total unit's capacity actually used),

- internal consumption of energy carriers (electricity and fuels),
- requirements of labor, land and water (either aggregate or per plant),
- significant types and quantities of waste/pollution generated,
- facilities' lifetime and construction time.

For example, in the South Africa case, the following technical coefficients have been considered for the following energy technologies:

Table II.3: Production factors used for the production of EC-MECHANICAL (electricity) for the most significant energy technologies in South Africa.

PES/Imports Category	**PES/Imports (using Eurostat nomenclature)**	**ET-t (GJ-EC/GWh)**	**ET-m (GJ-EC/GWh)**	**PCD-t (kW-REU/GWh)**	**PCD-m (kW-REU/GWh)**	**HA (h/GWh)[(a)]**	**WT (m3/GWh) [(a)]**	**LU (ha/GWh) [(a)]**
Solid Fuels	All	160	12	1.6	0.37	65	2,090	negl.
Nuclear	Nuclear Power [16_107030]	250	119	2.5	3.8	480	3,100	negl.

Source: own elaboration (for PCD); after case "Nuclear Energy without Reprocessing" in Diaz-Maurin and Giampietro, 2013 (see also Chap. 4) (for ET and HA); after EPRI, 2010 (for WT).

Note: (a) Requires being cross-checked against economic, water and land-use analyses.

Table II.4: Production factors used for the production of EC-THERMAL (fuels and heat) for the most significant energy technologies in South Africa.

PES/Imports Category	**PES/Imports (using Eurostat nomenclature)**	**ET-t (GJ-EC/GWh)**	**ET-m (GJ-EC/GWh)**	**PCD-t (kW-REU/GWh)**	**PCD-m (kW-REU/GWh)**	**HA (h/GWh)[(a)]**	**WT (m3/GWh) [(a)]**	**LU (ha/GWh) [(a)]**
Petroleum products	All	0.5[(b)]	negl.	0.005	negl.	negl.	negl.	negl.
Renewables	Biomass & Wastes [5540] - Biofuels	370	negl.	4.0	negl.	231	150	7.5

	(ethanol from sugarcane, Brazilian high input case)

Sources: after Giampietro and Mayumi, 2009 (for Biofuels); after SASA, 2010 (for HA of Biofuels).

Notes: (a) Requires being cross-checked against economic, water and land-use analyses; (b) ET-THERMAL corresponding to losses in Oil Refineries.

II.2 Logical framework

STEP #1: PES/Imports category split

Step 1 consists in distinguishing the three categories of energy products: (1) imports as GER, that are used for generating electricity; (2) imports as EC, that are directly consumed in the different sectors of society (End Uses); and (3) Primary Energy Sources, that are coming from local supply. In addition, exports of EC are identified so as to equilibrate the energy balances.

In this step, we only use data on energy statistics on imports and local supply (tab. II.1).

Table II.5: Distinction of imports and PES (South Africa, year 2009).

PES/Imports Category	PES/Imports (using Eurostat nomenclature)	Total PES/Imports (ktoe)	PES (ktoe)	Imports as GER (ktoe)	Imports as EC (ktoe)	Exports (ktoe)
Petroleum products	Crude Oil [3105][(a)]	24,384	150	24,234	as GER only	0[(c)]
	Feedstocks and other hydrocarbons [3190]	-	-	-	-	
	All petroleum products [3200]	6,298	as EC only	as EC only	6,298	-2,701[(c)]
	LPG [3220]	see [3200]	-	-	-	
	Motor spirit [3230]	see [3200]	-	-	-	
	Kerosenes - Jet Fuels [3240]	see [3200]	-	-	-	

	Naphta [3250]	see [3200]	-	-	-	
	Gas/Diesel oil [3260]	see [3200]	-	-	-	
	Residual Fuel Oil [3270A]	see [3200]	-	-	-	
	Other petroleum products [3280]	see [3200]	-	-	-	
Solid Fuels	All solid fuels [2000]	143,602	142,248	1,354	-	-45,234[(c)]
	Hard Coal and Patent Fuels [2112-2118]	see [2000]	-	-	-	
	Coke [2120]	see [2000]	-	-	-	
	Lignite and Deriv. [2200]	see [2000]	-	-	-	
Gas	Natural Gas [4100]	3,709	851	2,858	-	
	Derived Gas [4200]	-	-	-	-	
Nuclear	Nuclear Power [16_107030][(b)]	3,337	3,337	-	-	
Renewables	Hydro Power [16_107034]	125	125	-	-	
	All renewables, excl. Hydro	-	-	-	-	
	Wind Energy [5520]	-	-	-	-	
	Solar Energy [5530]	-	-	-	-	
	Solar Heat [5532]	-	-	-	-	
	Photovoltaic Power [5534]	-	-	-	-	
	Biomass & Wastes [5540] - Biofuels	14,429	14,429	-	-	-267[(c)]
	Geothermal Energy [5550]	64	64	-	-	
Energy Carriers	Electricity	1,057	as EC only	as EC only	1,057	-1,208[(d)]

Notes: (a) Input to Refineries; (b) Assuming all uranium from domestic supply; (c) exports as THERMAL; (d) exports as MECHANICAL.

STEP #2: GER (convention) and EC-split

Step 2 consists in evaluating the Gross Energy Requirement (GER) of each energy products as well as on obtaining the distribution between the different EC generated. For this purpose, we must track what the different energy products (PES and Imports) are used to generate (energy carriers as thermal or mechanical).

In doing so, since we are dealing with non-equivalent forms of energy (GER and EC; and THERMAL and MECHANICAL), the formal evaluation of GER therefore results from a convention over the equivalence between GER and GSEC. Using data from Sorman (2011) we can assume:

- GER/GSEC-THERMAL = 1.00
- GER/GSEC-MECHANICAL = 2.60 (1/0.385)

Note: In strict terms, the GER/GSEC ratios can be evaluated only after the End Uses have been characterized, which in turn requires a GER/GSEC equivalent ratio (impredicativity of energy analysis). As a matter of fact, these ratios only are used in order to provide an adequate split of EC. The final evaluation of GER will use the iterated GER/GSEC (after the EU are characterized), shown in tab. II.17.

For this step, we use for THERMAL energy, data on energy statistics on imports and local supply (tab. II.1); and for MECHANICAL energy, data on energy statistics on electricity generation and consumption (tab. II.2).

Table II.6: PES/Imports split to produce thermal and mechanical energy (South Africa, year 2009).

PES/Imports Category	**PES/Imports (using Eurostat nomenclature)**	**Total PES/Imports used to make MECHANICAL energy (ktoe)**	**Total PES/Imports used to make THERMAL energy (ktoe)**	**Total GSEC-m (GWh)**
Petroleum products	Crude Oil [3105]	-	24,384	-
	Feedstocks and other hydrocarbons [3190]	-	-	-
	All petroleum products [3200]	12	6,286	49

	LPG [3220]	see [3200]	see [3200]	see [3200]
	Motor spirit [3230]	see [3200]	see [3200]	see [3200]
	Kerosenes - Jet Fuels [3240]	see [3200]	see [3200]	see [3200]
	Naphta [3250]	see [3200]	see [3200]	see [3200]
	Gas/Diesel oil [3260]	see [3200]	see [3200]	see [3200]
	Residual Fuel Oil [3270A]	see [3200]	see [3200]	see [3200]
	Other petroleum products [3280]	see [3200]	see [3200]	see [3200]
Solid Fuels	All solid fuels [2000]	58,866	84,736	232,196
	Hard Coal and Patent Fuels [2112-2118]	see [2000]	see [2000]	see [2000]
	Coke [2120]	see [2000]	see [2000]	see [2000]
	Lignite and Deriv. [2200]	see [2000]	see [2000]	see [2000]
Gas	Natural Gas [4100]	-	3,709	0
	Derived Gas [4200]	-	-	-
Nuclear	Nuclear Power [16_107030]	-	-	12,806
Renewables	Hydro Power [16_107034]	125	0	1,452
	All renewables, excl. Hydro	-	-	312
	Wind Energy [5520]	-	-	(see above)
	Solar Energy [5530]	-	-	(see above)
	Solar Heat [5532]	-	-	(see above)
	Photovoltaic Power [5534]	-	-	(see above)
	Biomass & Wastes [5540] - Biofuels	89	14,340	1,035
	Geothermal Energy [5550]	5	59	58
Energy Carriers	Electricity	1,057	-	12,293

Table II.7: Energy carrier split using a convention on GER per energy products (South Africa, year 2009).

PES/Imports Category	**PES/Imports (using Eurostat nomenclature)**	**GER (convention) as THERMAL energy (PJ-GER)**	**GER (convention) as MECHANICAL energy (PJ-GER)[(a)]**	**X-t (THERMAL)**	**X-m (MECHANICAL)**
Petroleum products	Crude Oil [3105]	1,021	-	1.00	0.00
	Feedstocks and other hydrocarbons [3190]	-	-	-	-
	All petroleum products [3200]	263	0.46	1.00	0.00
	LPG [3220]	-	-	-	-
	Motor spirit [3230]	-	-	-	-
	Kerosenes - Jet Fuels [3240]	-	-	-	-
	Naphta [3250]	-	-	-	-
	Gas/Diesel oil [3260]	-	-	-	-
	Residual Fuel Oil [3270A]	-	-	-	-
	Other petroleum products [3280]	-	-	-	-
Solid Fuels	All solid fuels [2000]	3,548	2,171	0.62	0.38
	Hard Coal and Patent Fuels [2112-2118]	-	-	-	-
	Coke [2120]	-	-	-	-
	Lignite and Deriv. [2200]	-	-	-	-
Gas	Natural Gas [4100]	155	0	1.00	0.00
	Derived Gas [4200]	-	-	-	-
Nuclear	Nuclear Power [16_107030]	-	120	-	1.00
Renewables	Hydro Power [16_107034]	0	14	0.00	1.00
	All renewables, excl. Hydro	-	2.9	-	1.00
	Wind Energy [5520]	-	-	-	-
	Solar Energy [5530]	-	-	-	-
	Solar Heat [5532]	-	-	-	-
	Photovoltaic Power [5534]	-	-	-	-
	Biomass & Wastes [5540] - Biofuels	600	9.7	0.98	0.02
	Geothermal Energy	2.5	0.54	0.82	0.18

	[5550]				
Energy Carriers	Electricity	-	115	-	1.00

Notes: (a) Using Partial Substitution Method for PES/Imports used to generate mechanical energy (after Sorman, 2011).

Then, it becomes possible to express the GER-convention values per each energy product following the PES/Imports split made in step 1.

Table II.8: GER (convention) per PES/Imports categories (South Africa, year 2009).

PES/Imports Category	**PES/Imports (using Eurostat nomenclature)**	**Total PES/Imports (PJ-GER)**	**PES (PJ-GER)**	**Imports as GER (PJ-GER)**	**Imports as EC (PJ-GER)**
Petroleum products	Crude Oil [3105]	1,021	6	1,015	0
	Feedstocks and other hydrocarbons [3190]	-	-	-	-
	All petroleum products [3200]	264	0	0	264
	LPG [3220]	-	-	-	-
	Motor spirit [3230]	-	-	-	-
	Kerosenes - Jet Fuels [3240]	-	-	-	-
	Naphta [3250]	-	-	-	-
	Gas/Diesel oil [3260]	-	-	-	-
	Residual Fuel Oil [3270A]	-	-	-	-
	Other petroleum products [3280]	-	-	-	-
Solid Fuels	All solid fuels [2000]	5,719	5,665	54	0
	Hard Coal and Patent Fuels [2112-2118]	-	-	-	-
	Coke [2120]	-	-	-	-
	Lignite and Deriv. [2200]	-	-	-	-
Gas	Natural Gas [4100]	155	36	120	0
	Derived Gas [4200]	-	-	-	-
Nuclear	Nuclear Power [16_107030]	120	120	0	0
Renewables	Hydro Power [16_107034]	14	14	0	0
	All renewables, excl. Hydro	2.9	2.9	0	0
	Wind Energy [5520]	-	-	-	-
	Solar Energy [5530]	-	-	-	-

	Solar Heat [5532]	-	-	-	-
	Photovoltaic Power [5534]	-	-	-	-
	Biomass & Wastes [5540] - Biofuels	610	610	0	0
	Geothermal Energy [5550]	3.0	3.0	0	0
Energy Carriers	Electricity	115	0	0	115
	TOTAL	**8,023**	**6,456**	**1,188**	**379**
	share of total GER	***1.00***	***0.80***	***0.15***	***0.05***

STEP #3: GSEC and LOSSES

Step 3 consists in evaluating the Gross Supply of Energy Carriers (GEC) as THERMAL and MECHANICAL, as well as the LOSSES of distribution (considered as negligible for THERMAL energy) for each energy product. That way, it will be possible to evaluate the Net Supply of Energy Carriers (NSEC) generated by each PES/Import category.

Table II.9: GSEC and LOSSES per PES/Imports category (South Africa, year 2009).

PES/Imports Category	**PES (using Eurostat nomenclature)**	**GSEC**		**DISTRIBUTION LOSSES**	
		THERMAL (PJ-EC)	**MECHANICAL (PJ-EC)**	**THERMAL (PJ-EC)** [a]	**MECHANICAL (PJ-EC)**[b,c]
PHYSICAL GRADIENTS		**4,159**	**884**	**0**	**87**
Petroleum products	All petroleum products [3200]	6.3	negl.	negl.	negl.
Solid Fuels	All solid fuels [2000]	3,514	828	negl.	81
Gas	Natural Gas [4100]	36	-	negl.	-
Nuclear	Nuclear Power [16_107030]	-	46	-	4.5
Renewables	Hydro Power [16_107034]	-	5.2	-	0.51
	All renewables, excl. Hydro	-	1.1	-	0.11
	Biomass & Wastes [5540] - Biofuels	600	3.7	negl.	0.37
	Geothermal Energy [5550]	2.5	0.21	negl.	negl.

IMPORTS AS GER		**1,167**	**8**	**0**	**0.8**
Petroleum products	All petroleum products [3200]	1,014	0.14	negl.	negl.
Solid Fuels	All solid fuels [2000]	33	7.9	negl.	0.8
Gas	Natural Gas [4100]	120	-	negl.	-
IMPORTS AS EC		**264**	**44**	**0**	**4.4**
Petroleum products	All petroleum products [3200]	264	0.04	negl.	negl.
Energy Carriers	Electricity	-	44	-	4.4
	TOTAL	**5,590**	**937**	**0**	**92**

Notes: (a) assuming no THERMAL LOSSES; (b) Assuming 10% of distribution losses in grid for MECHANICAL energy only (source: OECD/IEA, 2011); (c) TJ-EC for MECHANICAL is the joule-equivalent of Wh (1 Wh = 3,600 J).

STEP #4: Characterization of the HYPERCYCLE

Step 4 consists in the characterization of the internal investment of energy carriers (conversion losses, as thermal energy and mechanical energy) and other production factors (power capacity, human activity, land use, water throughput) in the Hypercyclic part (EM sector) of the system.

In this step, we use the technical coefficients of each significant energy sources (see tab. II.3).

Then, it becomes possible to evaluate the Power Capacity Dissipative of the EM sector (not to be confused by the Power Capacity Hypercyclic, see Chap. 3), both for generating thermal energy (tab. II.10) and mechanical energy (tab. II.11).

Table II.10: Evaluation of the Power Capacity Dissipative used for the production of EC-MECHANICAL (electricity) for the most significant energy sources (South Africa, year 2009) – Using flow-based method.

Devices/Systems	**PCD type**	**ET_i (GJ-EC/TJ-EC)**	**μ (%)(a)**	**CL (%)(b)**	**OL (%)(c)**	**UF (%)**	**PCD_i (kW-REU/TJ-EC)**
Fossil-based power-supply systems	PCD-THERMAL	160	25%	100%	80%	80%	1.6
	PCD-	12	80%	100%	80%	80%	0.4

	MECHANICAL						
Nuclear power-supply systems	PCD-THERMAL	250	25%	100%	80%	80%	2.5
	PCD-MECHANICAL	119	80%	100%	80%	80%	3.8
Hydro power-supply systems	PCD-THERMAL	negl.	-	-	-	-	negl.
	PCD-MECHANICAL	negl.	-	-	-	-	negl.
Biomass power-supply systems	PCD-THERMAL	negl.	-	-	-	-	negl.
	PCD-MECHANICAL	negl.	-	-	-	-	negl.

Notes: (a) assuming 25% efficiency for THERMAL-based converters and 80% efficiency for MECHANICAL-based converters; (b) assuming converters producing energy carriers (EC) used at full capacity; (c) assuming 80% of operating load for converters used to produce EC.

Table II.11: Evaluation of the Power Capacity Dissipative used for the production of EC-THERMAL for the most significant energy sources (South Africa, year 2009) – Using flow-based method.

Devices/Systems	**PCD type**	**ET_i (GJ-EC/TJ-EC)**	**μ (%)$^{(a)}$**	**CL (%)$^{(b)}$**	**OL (%)$^{(c)}$**	**UF (%)**	**PCD_i (kW-REU/TJ-EC)**
Manufacturing of petroleum products	PCD-THERMAL	0.5	25%	100%	80%	80%	0.005
	PCD-MECHANICAL	negl.	-	-	-	-	negl.
Biofuels (ethanol from sugarcane)	PCD-THERMAL	370	25%	100%	80%	80%	3.7
	PCD-MECHANICAL	negl.	-	-	-	-	negl.

Notes: (a) assuming 25% efficiency for THERMAL-based converters and 80% efficiency for MECHANICAL-based converters; (b) assuming converters producing energy carriers (EC) used at full capacity; (c) assuming 80% of operating load for converters used to produce EC.

STEP #5: NSEC-EU bifurcation

Step 5 consists in characterizing the End Uses (EU) allocated to each PES/Imports category based on the evaluation of NSEC derived from steps 3 and 4. When focusing on energy supply issues, the EU can be characterized as the Dissipative part (all sectors considered except the EM sector) once both EC consumed by the Hypercycle (EM sector) and sent as Exports are evaluated.

In the example of the South Africa case, the EU can be characterized as the Dissipative part (all sectors except the EM sector) once both EC consumed by the Hypercycle (EM sector) and sent as Exports are evaluated.

Table II.12: Characterization of the End Uses (1/2) – South Africa case, year 2009.

PES/Imports Category	**PES (using Eurostat nomenclature)**	**NSEC**		**HYPERCYCLE (EM sector)**	
		ET-t (PJ-EC)	**ET-m (PJ-EC)**	**ET-t (PJ-EC)**	**ET-m (PJ-EC)**
PHYSICAL GRADIENTS		**4,159**	**797**	**100**	**4.2**
Petroleum products	All petroleum products [3200]	6.3	negl.	negl.	negl.
Solid Fuels	All solid fuels [2000]	3,514	747	37	2.6
Gas	Natural Gas [4100]	36	-	negl.	-
Nuclear	Nuclear Power [16_107030]	-	42	3.2	1.5
Renewables	Hydro Power [16_107034]	-	4.7	-	negl.
	All renewables, excl. Hydro	-	1.0	-	negl.
	Biomass & Wastes [5540] - Biofuels	600	3.4	60[(a)]	negl.
	Geothermal Energy [5550]	2.5	0.21	negl.	negl.
IMPORTS AS GER		**1,167**	**7.2**	**0.85**	**0.03**
Petroleum products	All petroleum products [3200]	1,014	0.14	0.50	negl.
Solid Fuels	All solid fuels [2000]	33	7.1	0.35	0.03
Gas	Natural Gas [4100]	120	-	negl.	-
IMPORTS AS EC		**264**	**40**	**0**	**0**
Petroleum products	All petroleum products [3200]	264	0.04	imports as EC	

Energy Carriers	Electricity	-	40	imports as EC	
	TOTAL	**5,590**	**845**	**101**	**4.2**

Note: (a) Assuming output/input of 10:1.

Table II.13: Characterization of the End Uses (2/2) – South Africa case, year 2009.

PES/Imports Category	**PES (using Eurostat nomenclature)**	**EXPORTS**		**DISSIPATIVE part (EU)**	
		ET-t (PJ-EC)	**ET-m (PJ-EC)[a]**	**ET-t (PJ-EC)**	**ET-m (PJ-EC)**
PHYSICAL GRADIENTS		**-1,119**	**-47**	**2,944**	**746**
Petroleum products	All petroleum products [3200]	-0.6	negl.	5.7	negl.
Solid Fuels	All solid fuels [2000]	-1,107	-45	2,371	699
Gas	Natural Gas [4100]	-	-	36	-
Nuclear	Nuclear Power [16_107030]	-	-2.5	-	38
Renewables	Hydro Power [16_107034]	-	-0.28	-	4.4
	All renewables, excl. Hydro	-	negl.	-	1.0
	Biomass & Wastes [5540] - Biofuels	-11	negl.	529	3.4
	Geothermal Energy [5550]	-	negl.	2	0.2
IMPORTS AS GER		**-100**	**-0.4**	**1,067**	**6.8**
Petroleum products	All petroleum products [3200]	-89	negl.	925	0.14
Solid Fuels	All solid fuels [2000]	-11	-0.4	23	6.7
Gas	Natural Gas [4100]	-	-	120	-
IMPORTS AS EC		**-23**	**-2.4**	**240**	**37.5**
Petroleum products	All petroleum products [3200]	-23	negl.	240	0.04
Energy Carriers	Electricity	-	-2.4	-	37.5
	TOTAL	**-1,242**	**-50**	**4,251**	**790**

Note: (a) Exports of electricity spread over all energy sources generating MECHANICAL energy.

Step #6: Characterization of REUD (DISSIPATIVE)

Step 6 consists in the characterization of the Requirements of End Uses in the Dissipative compartments (REUD) of the system, which correspond to the consumption of energy carriers (thermal and mechanical) and of other production factors (e.g. power capacity, human activity, land use, water throughput).

Table II.14: Characterization of the Requirement of End Uses Dissipative (South Africa, year 2009).

Part	Demand-side Sectors	REU-THERMAL (PJ-EC/y)	REU-MECHANICAL (PJ-EC/y)
WHOLE (n)	**-**	**4,352**	**794**
DISSIPATIVE (n-1)	*All compartments excl. EM*	*4,251*	*790*
HYPERCYCLE (n-1)	*EM sector*	*101*	*4.2*
LOSSES (n)	**-**	**0**	**92**
EXPORTS (n)	**-**	**-1,242**	**-50**

Table II.15: Evaluation of the Power Capacity Dissipative consuming energy carriers (South Africa, year 2009) – Using flow-based method.

Part	PCD type	μ (%)[(a)]	CL (%)[(b)]	OL (%)[(c)]	UF (%)	PCD (GW-REU)
WHOLE (n)	PCD-THERMAL	25%	100%	10%	10%	345
	PCD-MECHANICAL	25%	100%	5%	5%	403

Notes: (a) assuming 25% efficiency for THERMAL-based converters and 80% efficiency for MECHANICAL-based converters; (b) assuming converters consuming energy carriers (EC) used at full capacity; (c) assuming 10% of operating load for converters consuming thermal energy, and 5% of operating load for converters consuming mechanical energy.

Table II.16: Evaluation of the Power Capacity Hypercyclic generating energy carriers (South Africa, year 2009) – Using flow-based method.

Part	PCH type	CL (%)[(b)]	OL (%)[(c)]	UF (%)	PCH (GW-GSEC)
HYPERCYCLE (n-1)	PCH-THERMAL	100%	80%	80%	222
	PCH-MECHANICAL	100%	80%	80%	37

Notes: (a) assuming 25% efficiency for THERMAL-based converters and 80% efficiency for MECHANICAL-based converters; (b) assuming converters consuming energy carriers (EC) used at full capacity; (c) assuming 80% of operating load for converters used to produce EC.

STEP #7: GER (iterative) per PES/Imports categories

Step 7 consists in formal evaluation of the total Gross Energy Requirement (GER) of each PES/Imports categories (tab. II.18). For this purpose, we use the GER/GSEC ratios that derive from the characterization of the End Uses, hence different from the one used in step 2 as well as country- and year-specific (tab. II.17).

Table II.17: GER/GSEC ratio per EC-type (South Africa, year 2009).

GER/GSEC-THERMAL	GER/GSEC-MECHANICAL
1.02	2.61

Note: Excluding IMPORTS as EC for which there are no conversion losses.

Table II.18: TOTAL GER (WHOLE incl. LOSSES) per PES/Imports categories (South Africa, year 2009).

PES/Imports Category	PES/Imports (using Eurostat nomenclature)	WHOLE		TOTAL GER
		THERMAL (PJ-GER)	MECHANICAL (PJ-GER)	TOTAL (PJ-GER)
PHYSICAL GRADIENTS		**4,240**	**2,309**	**6,549**
Petroleum products	All petroleum products [3200]	6.4	negl.	6
Solid Fuels	All solid fuels [2000]	3,582	2,162	5,744
Gas	Natural Gas [4100]	36	-	36
Nuclear	Nuclear Power [16_107030]	-	120	120
Renewables	Hydro Power [16_107034]	-	14	14
	All renewables, excl. Hydro	-	2.9	2.9
	Biomass & Wastes [5540] - Biofuels	612	10	622
	Geothermal Energy [5550]	2.5	0.55	3
IMPORTS AS GER		**1,190**	**21**	**1,211**
Petroleum products	All petroleum products [3200]	1,034	0.36	1,034
Solid Fuels	All solid fuels [2000]	34	20.6	55
Gas	Natural Gas [4100]	122	-	122
IMPORTS AS EC		**269**	**116**	**384**
Petroleum products	All petroleum products [3200]	269	0.09	269
Energy Carriers	Electricity	-	116	116

TOTAL	**5,698**	**2,446**	**8,144**

STEP #8: DIAGNOSTIC of the energetic metabolism

Once the seven steps of the logical framework have been followed, it becomes possible to perform one further step corresponding to the formal characterization of the diagnostic of the energetic metabolism of the system. This step consists in summarizing information about the external view and the internal view (see sect. 5.2.1 of Chap. 5).

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Appendix III
Curriculum Vitae of François Diaz Maurin

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Curriculum Vitae

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Summary

François Diaz Maurin is an engineer with expertise in large-scale infrastructure projects in the French and the US nuclear industries. He recently joined the Integrated Assessment group of ICTA-UAB and works with Dr. Mario Giampietro on the energy supply issues.

Positions and Achievements

Dec. 2010c Institute of Environmental Science & Technology (ICTA)
Universitat Autònoma de Barcelona (UAB), Barcelona, Spain
Researcher & PhD Candidate

Thesis: The Viability and Desirability of Alternative Energy Sources: Exploring the Controversy over Nuclear Power.

2009–2010 AREVA NP, Inc. Boston, MA, USA

Structural & Mechanical Engineer

Project: Design Certification Licensing of the U.S. EPR™, a generation III+ nuclear reactor.

- Performed and coordinated dynamic structural analyses of the U.S. EPR™ reactor under accidental scenarios.

Project: Hanford Vitrification Plant (Hanford site, WA, U.S.A.), the world's largest radioactive waste treatment plant to vitrify Hanford's tank waste for the U.S. Department of Energy (DOE).

- Performed recirculation pump Finite Element Analysis (FEA).

- Performed verification and validation of an integrated software for the piping design stress analysis of the recirculation loop.

2007–2008 SETEC TPI Paris, France

Project: EPR™ reactor for Electricité de France (EDF) in France, the world's 2nd generation III+ nuclear reactor under construction.

Structural Engineer

- Performed calculations of reinforced concrete structures and anchor plates of the reactor pool liners.
- Managed the production of drawings of reinforced concrete structures.

Project Director Assistant

- Taken part in the supervision team (5 pers.) for the production coordination of offices in France, Tunisia, Morocco, and Egypt (145 pers.).
- Acted as liaison especially between the Tunisian and Egyptian production teams and BOUYGUES Construction.
- Prepared and led progress meetings before CEO Assistant of BOUYGUES TP (4,900 pers.), which is a subsidiary of BOUYGUES Construction.

Education

Feb. 2011 Institute of Environmental Science & Technology (ICTA) Barcelona,

Universitat Autònoma de Barcelona (UAB) Spain

Master in Environmental Studies **Research Project** (Modules 40436 & 41890)

Thesis: *The Problem of the Competitiveness of Nuclear Energy: An Energetic Explanation.*

June 2007 Department of Civil Engineering Rennes, France

INSA Graduate School

MSc Degree in Civil Engineering.

Thesis: *Soil-Structure Interaction Analysis of a Nuclear Building of the EPR™ reactor of Flamanville, France.* (1st Class Honors with Distinction)

June 2004 Department of Civil Engineering Rennes, France

Rennes Institute of Technology

1st Class Honors **BSc Degree** in Civil Engineering with Distinction.

Research Interests

Within the main topics of *societal metabolism* and *energy transitions*, my research deals with the application of the MuSIASEM approach (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) to the discussion about alternative energy sources. In particular, my PhD dissertation focuses on assessing the viability and desirability of nuclear energy by developing a new protocol to compare the quality of different alternative energy sources.

Keywords: societal metabolism, energy transitions, alternative energy sources, nuclear energy, integrated assessment, biophysical economics, post-normal science.

Publications

Book chapters

Giampietro, M. and Diaz-Maurin, F. (in press) 'The Energy Grammar Toolkit'. In: Giampietro, M., Aspinall, R.J., Ramos-Martín, J. and Bukkens, S.G.F. (Eds). Re-source Accounting for Sustainability: The Nexus between Energy, Food, Water and Land Use. Routledge series 'Explorations in Sustainability and Governance'. http://www.routledge.com/books/details/9780415720595/ (To Be Published 30th March 2014)

Diaz-Maurin, F. et al. (in press) 'South Africa's Emerging Economy'. In: Giampietro, M., Aspinall, R.J., Ramos-Martín, J. and Bukkens, S.G.F. (Eds). Resource Accounting for Sustainability: The Nexus between Energy, Food, Water and Land Use. Routledge series 'Explorations in Sustainability and Governance'. http://www.routledge.com/books/details/9780415720595/ (To Be Published 30th March 2014)

Papers in international journals

Diaz-Maurin, F. and Giampietro, M. (in press) Complex Systems and Energy. MS no. 01549. Online database on Earth Systems and Environmental Sciences. *Elsevier*.

Diaz-Maurin, F. and M. Giampietro (2013) A "grammar" for assessing the performance of power-supply systems: comparing nuclear energy to fossil energy. *Energy* 49: 162–177.

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Technical reports

Diaz-Maurin, F. (2012) Assessing the viability of power-supply systems: a tentative protocol, *Reports on Environmental Sciences*, Institut de Ciència i Tecnologia Ambientals (ICTA), Universitat Autònoma de Barcelona, 17 September 2012.

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URL: http://www.recercat.net/handle/2072/169668

Conference proceedings

Diaz-Maurin, F. (2011) Tentative Ideas to Explore the Viability of the Nuclear Option. In: Ramos-Martin J, Giampietro M, Ulgiati S, Bukkens, SGF (Eds.) (2011): *Can We*

Break the Addiction to Fossil Energy? Proceedings of the 7th Biennial International Workshop, Advances in Energy Studies 2010, 19–21 October, 2010, Barcelona, Spain. Universitat Autònoma de Barcelona. pp. 579-589.

URL:
http://www.societalmetabolism.org/aes2010/Proceeds/DIGITAL%20PROCEEDINGS_files/POSTERS/P_190_Francois_Diaz_Maurin_REV.pdf

Book reviews

Diaz-Maurin, F. (2013) Review of "Towards an Integrated Paradigm in Heterodox Economics: Alternative Approaches to the Current Eco-social Crises", Julien-François Gerber, Rolf Steppacher (Eds.). Palgrave Macmillan, London (2012). *Ecological Economics* 88c: 178-179.

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Other publications

Diaz-Maurin, F. Decreixement sostenible i Eficiència Energètica. *Revista SAM*, Vol. 21 Eficiència Energètica, Diputació de Barcelona, Servei de Medi Ambient. In press. (Catalan) – Invited author.

Diaz-Maurin, F. (2012) L'incertitude comme limite à la maîtrise des risques. *Interface* 113: 20-21. ISSN 0985-3537. (French)

Diaz-Maurin, F. (2012) Fukushima : limites anthropologiques à la complexité et risque d'effondrement sociétal. *Entropia* 12: 99-108. ISSN 1954-2437. (French)

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Diaz-Maurin, F. (2011) Fukushima: Consequences of Systemic Problems in Nuclear Plant Design. *Economic & Political Weekly (Mumbai)* 46(13):10–12. 26 March, 2011.

URL: http://www.epw.in/commentary/fukushima-consequences-systemic-problems-nuclear-plant-design.html

Diaz-Maurin, F. (2011) Eléments de réflexion sur la question de l’énergie. *Interface* 109:45–47. ISSN 0985-3537. (French)

URL: http://www.ingenieur-insa.fr/public/stockage/INTERFACE_109_WEB.pdf

Scientific and Administrative Services

Services to international journals

Member of the editorial board of Frontiers in Energy Systems and Policy as Review Editor (Nature Publishing group, not indexed yet).

Reviewer for *Energy* (Elsevier, ISSN 0360-5442), *Energy Policy* (Elsevier, ISSN 0301-4215) *Environmental Innovation and Societal Transitions* (Elsevier, ISSN 2210-4224) and *Energy Strategy Reviews* (Elsevier, ISSN 2211-467X).

Services to the research group

Assistant to the research group on Integrated Assessment: Sociology, Technology and Environment (IASTE) in charge of the group's finances and external diffusion of its activities.

Projects

Our Energy Futures

- Coordinator of *Our Energy Futures* (http://www.ourenergyfutures.org/ – English) and *El Nostre Futur Energètic* (http://elnostrefuturenergetic.cat/ – Catalan), a forum of discussion between people and experts from all around the world about different topics related to energy.

- Editor of *Nuclear Predicament: François' take on nuclear energy* on *Our Energy Futures*, a special page which intends, first, to provide insights about how the nuclear energy system functions from the inside and, second, to put the discussion into perspective showing the different possible perceptions of one aspect.

DegrowthPedia (2009–2011)

- Founder of *DegrowthPedia*, a new collaborative platform for information and education about degrowth (http://degrowthpedia.org/).

Conferences

Oral presentations

F Diaz-Maurin, J Cadillo Benalcazar, Z Kovacic, C Madrid, T Serrano-Tovar, J Ramos-Martín, M Giampietro. *It's all about semantics: The use of grammars for the multi-scale integrated assessment of the nexus between energy, food and water*. 2014 Global Land Project Open Science Meeting, 19-20 March 2014, Berlin, Germany. (Abstract accepted)

The Viability and Desirability of Alternative Energy Sources: Applying New Protocols in Sustainability Science. 3rd Annual European Postgraduate Sustainable Development Symposium, 13-15 February 2013, Naples, Italy.

Back to Reality-Checks: Achieving best practices in energy policy, ELEEP Talks, Emerging Leaders in Environmental and Energy Policy Summit of the Atlantic Council and the Ecologic Institute, 1 June 2012, Brussels, Belgium.

URL: http://www.youtube.com/watch?v=lL-vfXhSL5s&hd=1 (video of the talk)

Is Nuclear Power a Viable Alternative Energy Source? Applying new protocols in energy analysis, Web-meeting on Nuclear Power Viability, conCERNed for Humanity club, European Organization for Nuclear Research (CERN), 2 April 2012, Geneva, Switzerland.

URL: http://indico.cern.ch/conferenceDisplay.py?confId=184250

Fukushima, un any després: el nuclear en cuestión(es), La Fàbrica del Sol, Àrea de Medi Ambient de l'Ajuntament de Barcelona, 15 March 2012, Barcelona, Spain. (Invited speaker)

Chernobyl, Fukushima and Beyond: Reflecting on the Future of Nuclear Energy, ICTA-UAB Monday Seminar series, 9 May 2011, Barcelona, Spain. Speakers: Kozo Mayumi, François Diaz Maurin, Mario Giampietro, and Louis Lemkow. Chair: Katharine N. Farrell.

Learnings from an ongoing nuclear disaster & Conclusions about the viability of nuclear energy, ICTA-UAB seminar on the nuclear accidents of Fukushima, 21 March 2011, Barcelona, Spain. (Keynote speaker)

URL: http://sicom.cat/futurs/2011/04/05/ffukushima-nuclear-accident/ (video with subtitles in Spanish)

"Did we find a way safe and effective to store nuclear waste for thousands of years?", Response to questions from high-school students during the public discussion "Can we break the addiction to fossil energy?", 22 October 2010, CosmoCaixa Science Museum, Barcelona, Spain.

URL: http://www.uab.es/servlet/Satellite/videos/reproduccio-1192707516892.html?param1=10divulgacio&param2=40cienciessocials&param4=economia&url_video=1289893947572

Posters

Assessing the Viability and Desirability of Alternative Energy Sources, UKERC Summer School 2012, 17-22 June 2012, University of Warwick, UK.

URL: http://www.ukerc.ac.uk/support/tiki-download_file.php?fileId=2530

Tentative Ideas to explore the viability of the nuclear option, 7th Biennial International Workshop, Advances in Energy Studies 2010, 19-21 October 2010, Barcelona, Spain.

Don’t forget the rich: a strategy proposal to spread the idea of degrowth, 2nd International Conference on Economic Degrowth, 26-29 March 2010, Barcelona, Spain.

The degrowthpedia initiative – development plan, 2nd International Conference on Economic Degrowth, 26-29 March 2010, Barcelona, Spain.

Organization

8th LIPHE4 Summer School: Developing Toolkits for Analyzing the Nexus between Land, Water, Food, Energy and Population across Scales, 8-12 July 2013, Universitat Autònoma de Barcelona, Barcelona, Spain.

The Complexity Revolution in Sustainability Science and Governance. Symposium organized by the IASTE Research Group of the Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona (UAB), May 30, 2013 Casa de Convalescència, Barcelona, Spain.

7th LIPHE4 Summer School: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM): An innovative approach to energy analysis, 17-21 September 2012, Casa de Convalescència, Barcelona, Spain.

Energy transition and degrowth paradigm, Workshop at the 3rd International Conference on Economic Degrowth, 19-23 September 2012, Venezia, Italy.

Didactic activities

Tutor for the module *“Session 4.1: How to crunch numbers in practical applications: Energy grammar”* during the 8th LIPHE4 Summer School, 8-12 July 2013, Barcelona, Spain.

Tutor for the module *“Application of the multi-level grammar MuSIASEM*: *Assessing the quality of alternative energy sources”* during the 7th LIPHE4 Summer School, 17-21 September 2012, Barcelona, Spain.

Interviews and other public appearances

Press

Pronucleares que dejaron de serlo, La Vanguardia, Medio Ambiente, 24 April 2011.

URL: http://www.lavanguardia.es/internacional/20110317/54128627435/francois-diaz-los-gases-radiactivos-del-plutonio-del-reactor-3-son-los-mas-peligrosos.html (Spanish)

Els càlculs eren d'un accident nuclear cada 45 anys, però en 40 anys n'hi ha hagut cinc, El Temps, 29 March 2011.

URL: http://www.eltemps.net/web/index.php?option=com_k2&view=item&id=4905:els-calculs-eren-d-un-accident-nuclear-cada-45-anys-pero-en-40-anys-n-hi-ha-hagut-cinc&Itemid=255 (Catalan)

El campo japonés tardará mucho tiempo en recuperarse de la radiación, AND.es Lleida, 21 March 2011.

URL: http://www.adn.es/local/lleida/20110321/NWS-1214-recuperarse-radiacion-tardara-japones-tiempo.html (Spanish)

La UAB analitza la situació de la nuclear de Fukushima, Cerdanyola.info, 21 March 2011.

URL: http://www.cerdanyola.info/web/menu_principal/inici/noticies/2011/03/21/seminari_fukushima.html (Catalan)

François Díaz: "Los gases radiactivos del plutonio del reactor 3 son los más peligrosos", La Vanguardia, International, 17 March 2011.

URL: http://www.lavanguardia.es/internacional/20110317/54128627435/francois-diaz-los-gases-radiactivos-del-plutonio-del-reactor-3-son-los-mas-peligrosos.html (Spanish)

Radios

Qué significa el nivel 7 que ha sido elevado la catástrofe en Japón?, Radio France International, Redacción América Latina, 12 April 2011.

URL: http://telechargement.rfi.fr.edgesuite.net/rfi/espagnol/audio/modules/actu/201104/ENFOQUE_JAPON_NUCLEAR.mp3 (Spanish)

Ràdio Sabadell 94.6 FM, *A Bona Hora*, 23 March 2011.

URL: http://www.radiosabadell.fm/audio/110323_abh_japo.mp3 (Spanish)

Ràdio l'Hospitalet 96.3 FM, *Futurs*, 21 March 2011.

URL: http://digital-h.cat/c/document_library/get_file?uuid=3ce3da63-113c-46e1-83dd-61c4b851baed&groupId=10915 (Spanish, full)

URL: http://sicom.cat/futurs/2011/03/23/accidente-nuclear-fukushima-radiacion/ (Spanish, excerpts in video)

Comment convaincre les riches de consommer moins ?, Reporterre.net, 15 March 2011.

URL: http://www.reporterre.net/spip.php?article1042 (French)

Televisions

Interview in *Eduard Rodríguez Farré: "Radiació nuclear invisible i inodora, però devastadora"*, Televisió de Catalunya (TVC), Chanel 33, Singulars, 9 May 2011.

URL: http://www.tv3.cat/videos/3515170 (Catalan)

Pessimisme amb el futur de la fuita de Fukushima en un debat a la UAB (Pessimism about the future of the leak at Fukushima in a debate at UAB), Televisió de Catalunya (TVC), Chanel 3/24, Societat, 22 March 2011.

URL: http://www.3cat24.cat/noticia/1114266/societat/Pessimisme-amb-el-futur-de-la-fuita-de-Fukushima-en-un-debat-a-la-UAB (Catalan)

Languages

French:	Native
English:	Fluent
Spanish:	Fluent
Catalan:	Moderate

Address and contact

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Affiliations

Since 2012:	Executive Board Member of the Liphe4 Scientific Association (http://www.liphe4.org/)
Since 2011:	Member of the Emerging Leaders in Environmental and Energy Policy Network (ELEEP), a membership-only forum co-organized by the Atlantic Council and the Ecologic Institute. (http://eleep.youngatlanticist.org/)
Since 2010:	Member of Research & Degrowth (http://rd.degrowth.org/)

Personal interests

Underwater hockey

- Head coach of the club of Sabadell (Barcelona, Spain).
- Former coach of the club of the Massachusetts Institute of Technology (Boston, USA).
- Former player in the 2nd Division of the French National Championship (Club of Rennes)

References available upon request

Glossary

alternative energy source – A primary energy source claiming it has the potential to become a significant contributor (superior to 20 per cent) of the overall market in the local, regional, national or global energy supplies. The potential and quality of an alternative energy source can be assessed by performing an integrated assessment of its viability, feasibility and desirability. Examples of technologies claimed as being alternative energy sources are nuclear power, biofuels, photovoltaic power, wind power, hydrogen, etc. Currently the search for alternative energy sources is motivated by the depletion of affordable fossil energy resources. See also 'energy transition'.

complex energetics – An innovative approach to the systemic study of transformations among different energy forms able to deal with the specific characteristics of self-organizing dissipative systems.

complex system – A system that allows one to discern many subsystems, depending entirely on how one chooses to interact with the system.

dendrogram – An alternative analytical tool used in complex energetics able to generate a set of forced relations between multiple flows and multiple funds across scales.

desirability of a metabolic pattern – The congruence of the metabolic pattern (flow/fund ratios) at the level of end-uses (specific functions at the local scale, such as deployment of nuclear power generation, public transportation) to benchmark values of flow/fund ratios (expected features of the functions expressed) characteristic of given types of socio-economic systems. The desirability domain cannot be assessed using biophysical analysis as it depends on socio-economic dimensions related to human preferences, cultural values, social institutions, etc. As such it reflects the level of acceptance of the metabolic pattern by a given society taken as a whole, independently from its viability and feasibility in biophysical terms. Deliberating over the desirability of metabolic patterns therefore requires conducting a participatory process of decision making in order to deal with the problem of social incommensurability.

desirability of a primary energy source – The congruence of the characteristics of a primary energy source (flow/fund ratios) to benchmark values of flow/fund ratios at the level of the whole energy sector.

dissipative systems – All natural systems of interest for sustainability (e.g., complex biogeochemical cycles on this planet, ecological systems, human systems when analyzed at different levels of organization and scales beyond the molecular one); self-organizing open systems, away from thermodynamic equilibrium.

energetic transition (energy transition) – This encompasses the time that elapses between an introduction of a new primary energy source and its claim to a substantial share (20 per cent to 30 per cent) of the overall market, or even its becoming the single largest contributor or an absolute leader (with more than 50 per cent) in national or global energy supplies (after a definition by Vaclav Smil). See also 'alternative energy source'.

energy carriers – The various forms of energy inputs required by the various sectors of a society to perform their functions. Energy carriers are produced by the energy sector using primary energy sources. Examples of energy carriers include liquid fuel in a furnace, gasoline in a pump, electricity in a factory, and hydrogen in the tank of a car.

energy end-uses – This expression refers to the useful tasks/work performed by the various sectors of society when converting energy carriers into applied power. Examples of end-uses include moving goods, melting iron, building roads and air-conditioning rooms.

energy return on investment (EROI) – The EROI is a semantic concept useful for studying the quality of primary energy sources. According to Cottrell, 'societies adopted a new energy technology only if it delivered a greater energy surplus, and hence a greater potential to produce goods and services'. To implement this semantic definition while keeping information on non-equivalent forms of energy carriers, the concept of EROI is expressed by using a characterization of energy flows based on (1) the ratio between two vectors (representing flows of energy carriers as a mix of mechanical and thermal Joules), and also (2) as a ratio between two matrices (describing set of vectors of "end uses").

energy (supply) sector – The specialized sector of society whose goal it is to deliver the required mix of energy carriers to society using a given mix of primary energy sources and energy carriers. The mix of energy carriers supplied by the energy sector has to match in quantity and quality the demand of the various sectors of the society.

energy system – An integrated set of unit operations capable of generating a net supply of energy carrier using a given amount of primary energy sources. A power-supply system is an energy system specialized in the generation of electricity as an energy carrier.

epistemological complexity – Complexity that is at play every time the interests of the observer (the goal of the mapping) are affecting what the observer sees (the formalization of a scientific problem and the resulting model).

exosomatic metabolism – Technical conversions of different types of energy inputs (energy carriers) into end-uses that take place outside the human body, but under direct human control.

external constraints to metabolism – External constraints refer to the availability of favorable boundary conditions (gradients) required by the metabolic system in interacting with its context (outside view). E.g., an external constraint is present when the system has plenty of technical capital but it does not have enough primary energy inputs.

feasibility of a metabolic pattern – The compatibility between the requirement of primary energy sources on the supply side and the requirement of sink capacity on the waste side against their availability at the macro scale. The feasibility domain reflects the existence of external constraints.

feasibility of a primary energy source – The feasibility check of a primary energy source in relation with the whole energy sector.

fossil fuels – Liquid fuels generated from fossil energy. Fossil energy is organic material generated in prehistoric times and stored below the surface of the Earth.

fund/flow model for metabolic systems – Georgescu-Roegen proposed a fund-flow model useful for representing, in biophysical terms, the metabolism of socio-economic systems.
Fund elements are those that remain the same during the analytical representation (they reflect the choice made by the analyst when deciding what the system is and what the system is made of).

Flow elements are those that are either produced or consumed during the analytical representation (they reflect the choice made by the analyst when deciding what the system does and how it interacts with its context). Flow elements can be described in terms of relevant monetary, energy and material flows.

In this model, fund elements are metabolic converters; they must be able to maintain and reproduce themselves in order to keep their original identity. Thus, fund elements entail:

- an overhead on the flow they process, for their maintenance and reproduction;
- a definition of what should be considered as an admissible input (their identity entails that they can only metabolize a specified type of inputs); and
- a set of biophysical constraints on the relative conversion pace of metabolized flows (their identity can be associated with an expected power level).

For this reason, the fund-flow model is particularly suited to studying the energetic metabolism of socio-economic systems.

fund-flow energy supply (renewable energy sources) – A flow of energy originating from a fund does not imply a change in time of the characteristics of the system. For example, we can milk a healthy cow every day, and if we do not overdo it, the cow will remain healthy. A self-reproducing dairy farm – producing milk with sufficient calves guaranteeing the replacement of cows and enough pasture for feeding them – would represent a fund providing a stable supply of milk. As long as the fund is able to repair and reproduce itself, the resulting flow can be considered stable. Hence, this milk supply can be called a renewable resource.

hierarchical systems – Systems that are analyzable into successive sets of subsystems; when alternative methods of description exist for the same system.

hierarchy theory – "A theory of the observer's role in any formal study of complex systems" (Ahl and Allen, 1996, p. 29).

impredicative loop analysis – An alternative analytical tool used in complex energetics able to generate forced relations of congruence between the characteristics of the parts and those of the whole.

internal constraints to metabolism – Internal constraints refer to the ability to generate enough applied power (useful work) for carrying out the set of useful tasks (functions) required by the metabolic system (inside view). E.g., an internal constraint is present when the system does not have enough technical capital to take advantage of available energy inputs.

multi-purpose grammar – An alternative analytical tool used in complex energetics able to link non-equivalent descriptive domains by generating a set of expected relations between a given set of semantic categories and a given set of formal categories. A multi-purpose grammar can be tailored and calibrated so as to define the relevant characteristics of the system depending on other characteristics and new relevant qualities in the analysis.

multi-level/multi-dimension matrix – An alternative analytical tool used in complex energetics able to represent series of congruence constraints across levels and, “at the same time”, congruence constraints across dimensions in the analysis of the viability of a metabolic pattern. Its functioning is very similar to a Sudoku grid.

nuclear energy (nuclear power) – A primary energy source consisting in the use of sustained nuclear fission (technology) for generating electricity (energy carrier) based on the use of uranium (physical gradient). The use of other technology (nuclear fusion), favorable gradient (thorium) or the generation of other energy carrier (heat) are currently not available at large-scale. Therefore ‘nuclear energy’ and ‘nuclear power’ are alternatively used in the text.

nuclear energy system (nuclear power-supply system) – The description of nuclear power as an energy system.

nuclear (power) industry – The private or public institutions in charge of the maintenance and reproduction of the nuclear energy system. The nuclear industry includes reactor vendors, electric utilities and mining companies.

physical gradients – Naturally occurring processes used by primary energy sources to generate energy carriers. Examples of physical gradients include below-ground fossil energy reserves (coal, gas, oil) and mineral energy reserves (uranium, thorium), blowing wind, falling water, the sun and biomass. Physical gradients are measured in biophysical units (e.g. tons of coal, cubic meter of gas, tons of uranium, mass and speed of either blowing wind or falling water, intensity of sun radiation, tons of biomass). See also ‘primary energy sources’.

post-normal science – An expression proposed by Silvio Funtowicz and Jerome Ravetz to indicate a critical situation in the production and use of science for governance. In contrast with 'normal science' – as defined by Kuhn – a post-normal science situation indicates that 'facts are uncertain, values in dispute, stakes high and decisions urgent'. This implies changing the focus of the discussion from truth to quality by enlarging the variety of methods, criteria and actors involved in the assessment of the validity and relevance of the scientific output. In relation to sustainability science, this occurs when available narratives for explaining the present sustainability predicament are no longer valid, and validated narratives for making useful predictions about possible futures are not available.

primary energy sources – This expression refers to the energy forms required by the energy sector to generate the supply of energy carriers used by human society. A primary energy source corresponds to a specific conversion process turning a physical gradient (or import product) into a given energy carrier. According to the laws of thermodynamics, primary energy sources cannot be produced. They must be available to society in order to make possible the production of energy carriers. Examples of primary energy sources include coal, gas, nuclear power, PV, biofuels, etc. See also 'physical gradient'.

scale – The relation between the perception of a given entity and its representation.

societal metabolism – A notion used to characterize the set of conversions of energy and material flows occurring within a society that are necessary for its continued existence. This concept implies that we can expect given patterns of energy metabolism to be associated with the different structures and functions of a socio-economic system.

stock-flow energy supply (*non-renewable energy sources*) – A flow of energy originating from a stock entails a change in the characteristics of the system. If we start with a stock of 1000 units and we consume for one year a flow of 100 units per year, the stock from which we obtained the input will have changed its identity. After one year, the original stock of 1000 units will have become a stock of 900 units. For this reason we can call the supply of a given input coming from a stock-flow a non-renewable resource. See also 'nuclear energy'.

technological lock-in – A situation that occurs when a technical solution has been generated by a mistaken narrative. This awkward situation can easily become a lock-in because, often, brilliant technical solutions require considerable financial investments. For this reason, even when experience shows that the original idea was a bad one, nobody dares to halt the deployment of the technical solution. A famous example of a technological lock-in in the airline industry is the so-called “Concorde syndrome” that is the name given to the failed experience of the supersonic passenger airliner.

unit operations – Functions corresponding to the production rules of an energy system. The four standard functions describing the unit operations of electricity generation in power-supply systems are: (1) Mining; (2) Refining/Enriching; (3) Generating power; and (4) Handling waste/Controlling pollution.

viability of a metabolic pattern – The congruence of the characteristics of flow and fund elements across the micro and meso scale. The viability domain reflects the existence of internal constraints.

viability of a primary energy source – The viability check of a primary energy source in relation with the whole energy sector.