SUPPORTING ENERGY DECISION-MAKING: A MULTICRITERIA ANALYSIS OF FRANCE’S 2025 ELECRICITY GENERATION SCENARIOS

A Thesis

by

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ABSTRACT

In December 2012, France, the world's most nuclear-powered country on a per capita base, has initiated a national debate on energy transition. In the wake of Fukushima nuclear accident and following the nuclear phase-out of neighboring countries such as Germany, Belgium, and Switzerland, François Hollande, who were to be the next president promised that France will reduce the share of nuclear in total electricity generation from 75% to 50%. However, this decision involves complex conflicting trade-offs among its economic, environmental, and social consequences. Indeed, there is no ideal energy technology that performs well according to all of these sustainability pillars but rather each of them participates in the mitigation of a specific energy issues while nourishing another. At the same time, in France like in most nuclear-powered countries, the decision-making process of energy policies lack transparency. Energy decisions are made by multiple decision-makers that have different agendas and no expertise in the energy-related fields. As a result, there is a need to provide an academic support to ensure that energy decision-making in France is conducted towards an improvement of the sustainability of the energy supply system.

Previous studies have applied decision support technique to provide a structured analysis of energy decision options against multiple objectives all over the world. Multi-Criteria Analysis (MCA) has been seemingly adopted by the scientific community as the new standard analytical framework for decision support. MCA has the capacity to deal with a broad range of economic, environmental, and social concerns and integrate them in the decision-making process so that the solution optimally fitting decision-makers' objectives and preferences is found. However, in the case of France, academic attention in energy decision support is scarce and energy decision support studies are conducted by a government-ordered commission of experts. In 2011, a

comparative analysis of electricity generation scenarios for 2050 were conducted but turned out to be very controversial as independent energy experts' critiques pointed out the two main issues: their lack of objectivity and the limitation to an economic approach of energy decisions. Indeed, most of the scenarios assessed were from the industry involvement and independent experts revealed a number of factual mistakes and methodological bias. Furthermore, the decision criteria focusing on economic concerns and socio-environmental impacts were assimilated to local CO2 emissions and acceptance of the noise from wind turbines. The issue of nuclear wastes disposal or safety of the power plant were barely mentioned. Decision support in France appears therefore as behind the academic standard of decision support in term of both structure and integration of socio-environmental aspects.

The objective of this study is to evaluate the energy transition plan in France while filling the gaps of the previous French energy decision-support studies. The present study has been built on the MCA framework. Among the potential 2025 electricity supply strategies, the four categories were identified leading to the elaboration of four representative scenarios. The life extension of historical nuclear power plants is represented by the Business-As-Usual (BAU) scenario. Furthermore, three transition scenarios were built. First, a slow transition (SLO) scenario to less nuclear power that represents an acceleration of the commissioning of third generation of nuclear reactors. Then, two direction of nuclear energy share reduction to 50% by 2025 were analyzed: 50% nuclear with High Renewable Energies (HRE) scenario and the 50% nuclear with High Fossil Fuels (HFF) scenario. Then, the four scenarios were assessed from the perspective of electricity generation costs based on Levelized Cost Of Electricity (LCOE) calculations and of socio-environmental impacts gathered in five categories: impact on ecosystems, resources availability, human health, hazardous waste, and safety. Finally, a trade-offs analysis between the economic performance of scenarios and their socio-environmental impacts were conducted at

three different levels of scale, from overall trade-offs to detailed bi-dimensional trade-off of costs against each socio-environmental indicator.

The result showed that the decision of whether to initiate the transition itself is subjected to significant compromise. Indeed, the BAU scenario represents a very cost competitive option and has the lowest impacts on ecosystems and health as well as climate change. Nevertheless, the issues of radioactive waste, ionizing radiations and accidental consequences are particularly significant with this scenario. As for SLO transition scenario, it is at the core of trade-offs between very high cost and maximum accidental consequences, still high radioactive waste generation and relatively low greenhouse gases emissions compared to other transition scenario. As for, HRE transition scenario, it involves moderated cost socio-environmental impacts except for climate change and ozone depletion, which are very high. HFF transition scenario has very high impact according to almost every socio-environmental scenario but is also the least expensive transition scenario. But, for HRE and HFF, the nuclear-related impacts such as nuclear wastes, maximum accidental consequences and ionizing radiations are logically decreasing along with nuclear energy share in the mix. Furthermore, the internal analytical results were confronted to external aspects related to the economic context (financial crisis, energy industry, volatility of fuel prices or employment), the environmental context (climate change, radioactive waste) and the socio-political context (acceptance, electricity exports, diplomacy).

As an outcome, this study proposes a combination of the trade-offs analytical results and contextualization factors in the form of easy-to-understand SWOT analysis for each scenario. Recommendations to decision-makers include the improvement of the transparency of the decision-making process in order to make possible a concrete integration of decision support studies. Also, socio-environmental concerns in the decision-making process should be systematically included in energy decision-making processes as they are too often informally

considered leading the way to hasty generalizations and subjectivity. Further research should also follow those direction by extending the present study effort to the development of a decision-making support framework based on decision-makers’ interests and preferences..

ACKNOWLEDGEMENTS

Several people have contributed to improving the quality of this thesis. First, I would like to express my gratitude to my advisor Project Associate Professor Yarime Masaru for the directions, remarks and trust through the learning process of this master thesis.

This thesis completion depends largely on the encouragement and guidelines of two people. I would like to show my greatest appreciation and admiration to my co-advisor, Assistant Professor Tomohiro Akiyama. I can’t say thank you enough for his tremendous support and help. I feel motivated and encouraged every time I attend his meeting. Without his encouragement and guidance this project would never have materialized. To Assistant Professor Jia Li, I would like to show my deepest and sincere gratitude for the numerous fulfilling discussions we had. She kindly shared with me her original and often brilliant perspectives on many topics, both academic and personal. This research would never have been completed without her determination and enthusiasm.

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It would not have been possible to write this master thesis without the help and support of the faculty member of GPSS who helped me with great patience during the two years of my master. I would also like to show my appreciation to the University of Tokyo and to MEXT who gave me the opportunity to study two years in Japan and offered me a scholarship. That was an unforgettable experience.

Above all, I would like to thank my loved one, who have supported me throughout entire process, by keeping me harmonious and helping me putting pieces together. I will be grateful forever for your love, Catarina.

I would like to address a special thanks to the kind people around me in GPSS, and to my friends waiting for me in France. Ludwig, I am not sure you really deserve to be named here, but I thank you for making so much of my time unproductive. We always had fun together no matter the distance or work load.

For any errors or inadequacies that may remain in this work, of course, the responsibility is entirely my own.

DEDICATION

I would like to dedicate this academic achievement to my family for their constant support and encouragements. My parents, Chantal and Jean-Claude and my sister, Cyrielle helped me shape my vision of sustainability long before I joined GPSS. Certainly, this thesis work would never have been possible without them.

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LIST OF ABBREVIATIONS

BAU	Business-As-Usual scenario
CBA	Cost-Benefit Analysis
CdC	Cours des Comptes
EC	European Commission
ENSAD	Energy-related Severe Accident Database
EPR	Eurepean Pressurized Reactor
FF	Fossil Fuels
HFF	50% nuclear with High Fossil Fuels transition scenario
HRE	50% nuclear with High Renewable Energies transition scenario
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IRENA	International Renewable ENergy Agency
LCA	Life Cycle Analysis
LCIA	Life Cycle Impact Asessment
LCOE	Levlized Cost Of Electricity
MCA	Multi-Criteria Analysis
MCDA	Multi-Criteria Decision Analysis
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
OPECST	Office Parlementaire d’Évaluation des Choix Scientifiques et Technologiques
PSI	Paul Scherrer Institut
RE	Renewable Energies

LIST OF ABBREVIATIONS (continued)

RTE	Réseau de Transport d’Électrcité
SLO	Slow transition scenario
UFE	Union Française de l’Électricité
UNCSD	United Nations - Comission on Sustainable Development
WNA	World Nuclear Association

PREFACE

This thesis has been submitted in partial fulfillment of the requirements for the Master's degree in Sustainability Science at the Graduate Program in Sustainability Science of the Graduate School of Frontier Science at The University of Tokyo, Japan. The work has been carried out from October 2011 to July 2013. The topic of this thesis is *Supporting Energy Decision-Making*: A *Multi-Criteria Analysis* (MCA, hereafter) of *France's 2025 Electricity Generation Scenarios*.

The three concepts were italicized to emphasize some essential delimitations of the thesis. Firstly, *'Supporting Energy Decision-Making'* refers to both the objective and the target of this thesis as it aims at providing decision-makers with necessary structure, information and understanding of potential solution to an energy decision. Secondly, *'MCA'* refers to the decision support framework used in this thesis. It means, in this context, that a broad range of criteria of decision both economic and socio-environmental were traded off in the analysis of electricty mix scenarios. Thirdly, *'France's 2025 Electricity Generation Scenarios'* means that the focus of the thesis will be on the support of France's electricity supply system planning for 2025. It is referring to the energy transition debate initiated by President Hollande after his commitment to reduce the share of nuclear energy from 75% to 50% in May 2012. The thesis consists of five chapters, which are organized as follows:

- 'Introduction', which introduces the problem of electricity generation transition and decision-making support in France. Previous researches related to decision-making support for energy decision are also presented.

- ‘Methodology’, which describes the methodology of MCA from the scenario building, the economic and socio-environmental assessments to the trade-offs analysis.
- ‘Results’, which presents the analytical results obtained through the trade-offs analysis.
- ‘Discussion’, which discusses the interpretation of the results and contextualize them scenario by scenario.
- ‘Conclusion’, which summarizes this study, points out its limitations, and propose directions for future areas of research.

1

INTRODUCTION

1.1 Background

1.1.1 Energy transition in France

In the wake of Fukushima Dai-ichi nuclear accident, most European nuclear-powered countries made concrete plans to phase out nuclear but France is still debating on its direction of transition. France dedicated itself to the full nuclear strategy after the first oil crisis of 1973 to insure energy independency (WNA, 2013). The country gradually became the largest producer of nuclear power on per capita base, with nuclear energy accounting for 77% of its electricity production in 2011 (Figure 1.1). With the development of the third generation of nuclear power plant, the European Pressurized Reactor (EPR), France is, more than ever, investing in its nuclear activity not only within the domestic market, but also with international ambitions. After Fukushima's nuclear disaster, most European nuclear-powered countries decided to head for a phase-out of nuclear power. Between May and June 2011, Germany, Belgium, Switzerland and Italy gradually decided to abandon their nuclear activities, pressuring France to follow their lead[1]. In addition to this foreign pressure, nuclear energy became less and less accepted among the general public domestically with 77% of French people favoring a more or less rapid phase-out of nuclear in June 2011[2]. As a result, during the presidential election campaign, François Hollande, the main left-wing candidate, promised to decrease the share of nuclear power in the French

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[1] On March 2011, the German Local Commission of Information and Surveillance (LCIS) filled a request for a moratorium for Fessenheim plant, the oldest nuclear power plant located 2km away from the German borders(Nückles, 2011).

[2] According to an Ifop poll in June 5, 2011, 77% of French people want a more or less rapid phase out of nuclear including 62% advocating a gradual stop in 25 or 30 years, and 15% want an immediate stop (IFOP, 2011).

electricity mix to 50% by 2025. In May 2012, Hollande defeated the right-wing pro-nuclear candidate and started a public debate on energy transition in December 2012 with the objective of discussing the different French electric generating fleet development options.

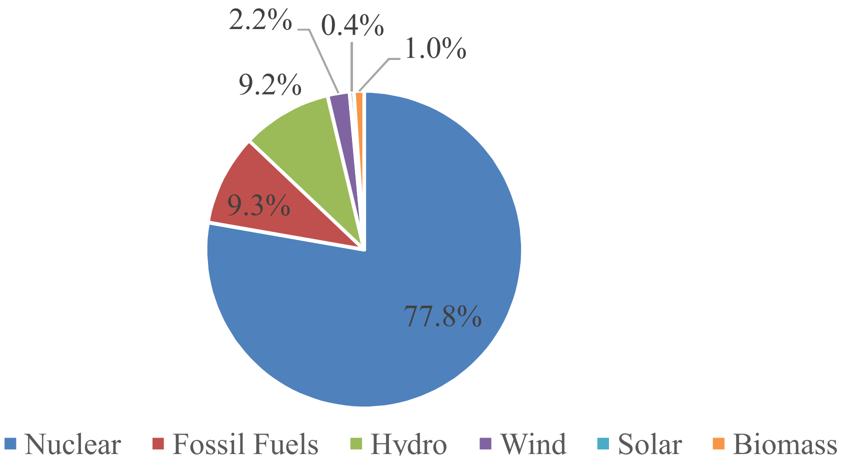

Fig. 1.1: French electricity mix in 2011 (Réseau de Transport d'Électricité, 2012)

1.1.2 Decisions under multiple conflicting objectives

However, such transition regarding energy policy decisions is complex as decision makers have to take into account multiple, often conflicting, goals including economic, environmental, and social objectives. Indeed, the advent of energy-related global problems such as climate change or nuclear safety gives general priorities in energy decision-making. At the same time, as shown in Figure 1.2, the consequences of energy decisions are broad and linked to numerous other concerns that are also significant to decision-makers. Energy decisions are then to be approached under the constraint of multiple objectives, conciliating energy strategy with other common political imperatives such as health or employment. This situation is all-the-more complex as those objectives are conflicting with each other. The alternatives choices involving numerous energy sources such as nuclear energy, fossil fuels, or renewable energies (e.g., wind and solar), are exploited with quickly evolving energy technologies. All of those technologies are characterized by attributes related to their economic performances, and their environmental and social impacts. Each energy technology performs better according to some of this attributes and are then a solution to specific energy-issues (e.g. nuclear power doesn't emit much CO_2 and can then be used to tackle climate change). But, at the same time they have attributes that nourish other energy issues (e.g. nuclear power generate massive amount of radioactive waste). Consequently, multiple conflicting objectives and trade-offs among those objectives should be comprehensively addressed by decision-makers.

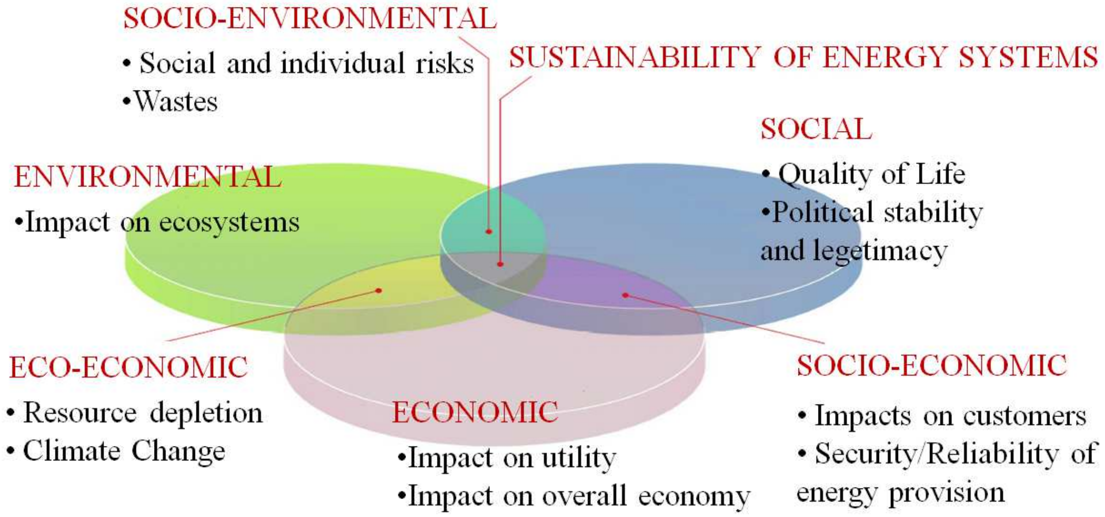

Fig. 1.2: Energy decision related concerns (Hirschberg et al., 2008)

1.1.3 Decision-makers' perspective

Another challenge lays in the fact that energy decisions are made by multiple decision-makers with different agendas and no expertise in energy issues. It is often taken for granted that decision-makers are politicians representing the will of the citizens who elected them as described in the mean vote theory. However, practically, in the case of nuclear-powered countries, Hymans (2012) observed that decisions are often taken in a more elitist sphere called the iron triangle where politicians, bureaucrats, and businessmen favor each other in the pursuit of personal agendas (Figure 1.3). Those multiple stakeholders' involvement in energy decisions has led to a lack of transparency in the decision-making process. Stakeholders in energy decision-making, their role and their preferences and interests are not formally known to the public. This lack of transparency also extends to the availability of information concerning real impacts of energy options. This has resulted in a tendency to "focus on alternatives rather than on values, fundamental objectives and tradeoffs among those objectives, even though they are inconsistent" (Slovic and Lichtenstein, 1971). Additionally, when confronting to the complexity of energy decision-making, decision-makers have "only general priorities and vague notions of how much of an aspect they are willing to give up for another" (Fischer, 1979). The political elite is usually not a specialist of energy issues and whenever energy decisions involve numerous attributes, research in behavioral decision theory has shown that they become inconsistent in their subjective evaluations of the options (Shepard, 1964). Often, "their mind will focus on two or three attributes, ignoring the others or it flit inconsistently among the attributes". All of these endeavors of research have shown that energy decision processes "lack a logical framework for defining alternatives, comparing their performance on important objectives, and considering different viewpoints" (Thomas and Samson, 1985). As a consequence, energy decisions are made by multiple stakeholders suffering from inconsistencies in their evaluation of options within a complex decision-making process lacking both logic and structure.

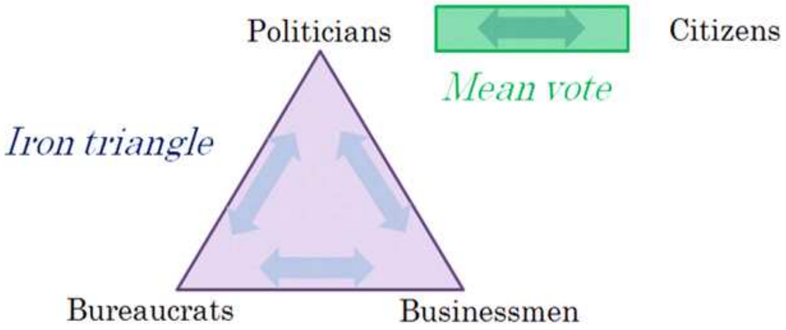

Fig. 1.3: Energy decision-makers: iron triangle against mean vote theory (Hymans, 2012)

1.2 Previous studies

1.2.1 State of the art in energy decision-making support

In light of the above, researchers have developed decision support techniques aiming at providing a structured analysis of energy decision options against multiple objectives. Indeed, to support decision-makers dealing with complex decisions, researcher developed two different types of decision analysis techniques (UK-DCLG, 2012). The first type encompasses monetary-based techniques, where the performances of each of the analyzed options are monetized and the least expensive solution is sought. The second one gathers the Multi-Criteria Analysis (MCA, hereafter) techniques, that explicitly deal with multiple criteria informing decision-makers of the trade-offs implied by each alternative. MCA has the capacity to indicate to decision-makers the solution that best suit them based on their objectives and preferences. However, in energy decision-making, the advent of multiple conflicting objectives has led researchers and leading energy institutions to integrate a broad range of social and environmental concerns in their support studies. Tables 1.1 and 1.2 recapitulates the efforts on carrying out a set of socio-environmental indicators for decision-making support and application of decision support techniques integrating socio-environmental concern for various energy systems around the world. There is a clear trend of increased attention on socio-environmental integration in decision support aiming at addressing decision-makers' conflicting objective issue. As a result of this trend in energy decision support, the monetary-based techniques are being abandoned in favor of multi criteria techniques. Indeed, even though monetizing methods were adapted to include socio-environmental aspects into Cost Benefit Analysis (CBA), they include controversial features. CBA has been criticized for being morally and intellectually irresponsible due to the monetization of human life value[3], which is

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[3] As an example, in 1979 the US-based Nuclear Regulatory Commission (NRC) used a value of 1,000 US$1979 per whole body-remains in its CBA (Baram, 1979)

necessary to monetize health and safety aspects (Baram, 1979). As a result, the application of monetary techniques on decision support when dealing with socio-environmental concerns has become scarce. The recognitions of these limitations lead the scientific community to adopt MCA techniques when dealing with decisions including socio-environmental concerns, multiple conflicting objectives, and trade-offs among those objectives such as energy planning decisions (Hobbs and Meier, 2000).

Tab. 1.1: Set of socio-environmental indicators for decision-making support

Study	*Source*
New Energy Externalities Developments for Sustainability	Hirschberg et al., 2008
United Nation Commission on Sustainable Development	
Energy Indicators for sustainable development	UNCSD, 2007
OECD Core Environmental Indicators	
Post Barcelona – Beyond Barcelona	IAEA et al., 2013
	OECD, 2003
Swiss Federal Office of Energy’s indicators for the energy sector	Spangenberg and Hinterberger, 2002
Baltic 21	PSI, 2012
Sustainability indicators to evaluate nuclear energy technologies	Baltic 21, 2000
Indicators of Sustainable Development	OECD et al., 2000
	Eurostat, 2005

Tab. 1.2: MCA application in academic journals

Study	*Source*
Germany	Hirschberg et al., 2004b
Switzerland	PSI, 2012
China	PSI, 2006
Nigeria	Gujba et al., 2011
Finland	Häyhä et al., 2011
Belgrade	Jovanović et al., 2009
Crete	Tsoutsos et al., 2009
UK	Hunt et al., 2013
Portugal	Ribeiro et al., 2013
Turkey	Hong et al., 2013
Japan	Boran et al., 2013

1.2.2 Energy decision analysis in France: a controversial matter

However, in the case of France, academic attention in energy decision support is scarce despite the case involves two main challenges addressed in the section 1.2.1. Indeed, energy support studies have been conducted by a commission mandated by the government to analyze the different alternatives' performances and impacts (Percebois (2012); Syrota (2008)). The results of the commission are highly controversial, as critiques pointed out the lack of objectivity and presented solemnly an economic approach to energy decisions.

Gap 1: *Structure of decision-making support in France*

The last energy decision support study, Energies 2050 (Percebois, 2012), turned out to be heavily criticized for its bias and shallowness as a consequence of its lack of structure and transparency. Indeed, decision support studies are traditionally conducted by the commission was not based on any of the analytical method used in the literature, but rather on partial comparisons and non-transparent evaluation processes. Independent energy experts led by Global Chance have listed up all the “methodological bias, factual mistakes and ideological tricks” included in the report (Desssus, 2012). As a matter of fact, the commission evaluated 26 electricity generation scenarios mostly from industries involved in nuclear activities, which led to Global Chance accusations of producing biased reports. Moreover, experts stressed that it “is the first time such a commission of experts does not develop its own scenarios and simply compare the scenarios published by the various stakeholders of nuclear power in France” (Desssus, 2012). Consequently, the 26 scenarios compared were formulated on very different and non-transparent hypothesis that prevent them to be formally compared. The analysis of the commission ended up to be shallow and subjective (Desssus, 2012). What's more, critical questions such as the demand reduction possibility were evicted from the commission report and depicted as “impossible and unwanted” (Percebois, 2012) without any other form of argumentation. Thus, there is a gap between the structured decision support that energy institutions and expert are struggling to implement and the non-transparent and subjective decision support in France.

Gap 2: *Inclusion of socio-environmental concerns in energy decision-making support*

Furthermore, the aspects included in the decision-support analysis were limited to the minimum in France: the commissions focused mainly on economic aspects, and greenhouses gas emissions. Those scenarios were examined according to a number of aspects such as production costs, electricity prices, impact on employment, energy security, social acceptance, and greenhouse gases emissions. They were also contextualized according to the forecast of electricity demand, the energy policy evolutions in Europe, the volatility of fossil fuels prices, and the energy resources geopolitics. On the other hand, social concerns include only the acceptance, which is not used as a decision criterion in the scenario evaluation but only to emphasize the low acceptance of noise produced by wind turbine. As for environmental aspects, they are assimilated to local CO2 emissions only (Percebois, 2012). Furthermore, the issues of final disposal of nuclear wastes and nuclear safety are avoided, whereas they are essential in the post-Fukushima era. Indeed, Global Chance observed that “nuclear safety is set as an unavoidable necessity and as such it is put as acquired and pointless to discuss” even though worldwide experts, after Fukushima, put into question nuclear safety including the Institute for Radiological Protection and Nuclear Safety (IRSN) who claimed that “it is now time to imagine the unimaginable” (Desssus (2012); Patel (2011)). However, the need for an inclusion of broader socio-environmental criteria was pointed out by the Cours des Comptes (CdC), the highest accounting authority in France, as concluding remarks in its cost assessment of the nuclear industry in France. They emphasized “the importance of the externalities which cannot be quantified, notably the impact on the environment, health, jobs and the trade balance, make it clear that costs are certainly not the only variables to consider in taking decisions regarding nuclear power generation" (CdC, 2012a).

1.3 Objective and significance of this study

The objective of this study is to examine energy transition in France while filling the gaps of the previous French energy decision-support studies. As a result, this research aims at supporting the decision-making process related to the reduction of the share of nuclear power from 75% to 50% by conducted a MCA that integrates a broader range of socio-environmental concerns to reveal their trade-offs against economic performances. As a result, information will be provided to help decision-makers debating and answering the two following research questions:

- Should we reduce the share of nuclear to 50% by 2025?
- How to reduce the share of nuclear to 50% by 2025?

The contributions of this research include the following:

1. An identification and structuring of electricity generation transition's problems and a critical analysis of current decision-making support in France
2. The building of scenarios representative of potential strategies of the electricity generation planning for 2025
3. A cost assessment and socio-environmental assessment based on Life Cycle Impact Assessment (LCIA) and previous studies of those scenarios
4. A trade-offs analysis that reveals the conflicts between the decision objectives.
5. An interpretation and contextualization of the results for each scenario

We believe, even though the thesis will focus on French conditions, many of the issues and the proposed energy decision-making support strategies are also applicable outside of France.

2

MATERIALS AND METHOD

2.1 Theoretical framework

This research has been designed based on the Multi-Criteria Analysis (MCA) framework. According to UNFCC, “MCA describes any structured approach used to determine overall preferences among alternative options, where the options accomplish several objectives.” (UNFCC, 2001). According to Hobbs and Meier (2000), it includes 10 steps (Fig. 2.1). The first 4 steps are similar to sustainability assessment of energy options. The possible alternatives are listed up and the criteria of analysis are identified based on the issues, one would like to mitigate. Then based on an impact model, the options are analyzed according to each criterion. MCA differs from a simple assessment as it extend to trade-offs analaysis (step 5) with the aim of communicating to decision-makers the trade-offs against the conflicting objectives implied in the decision-making process. From step 7, MCA develops itself into Multi Criteria Decision Analysis (MCDA). Indeed, impact quantified are scaled to simplify the comparison and weighed according to decision-makers preferences. If several weighting method were used, at the amalgamation step (9), they are combined into a single overall indicator using amalgamation rules. Eventually, the differences between methods and among stakeholders of the decision-making process are resolved (step 10) through the search for a consensus during negotiations. Thus, the most suitable solution according to decision-makers’ preferences is sought.

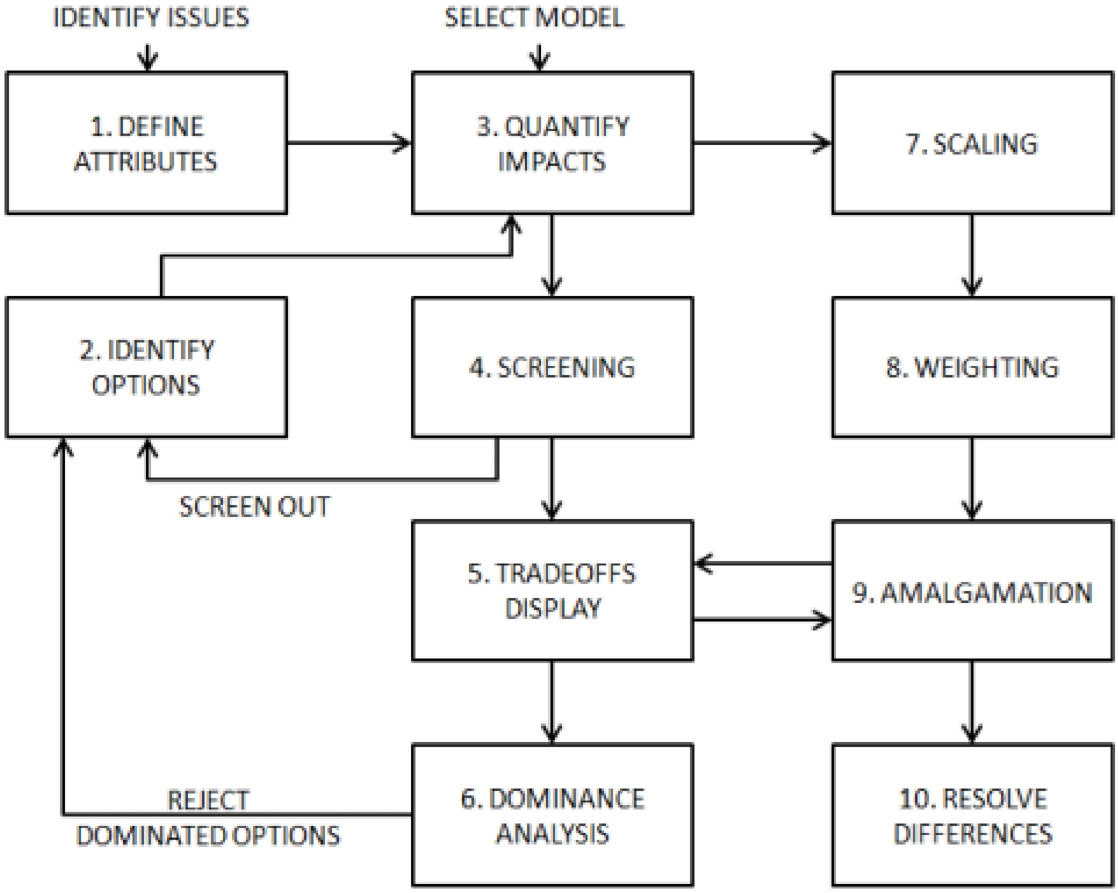

Fig. 2.1: Multi-Criteria Decision Analysis process (Hobbs and Meier, 2000)

As mentioned in section 1.1.3, because of the lack of transparency in the decision-making process, it was not possible to include decision-makers' perspective and preferences in this decision support study. However, according to (Hobbs and Meier, 2000), many MCA applications in the energy sector consider trade-offs analysis as the end-product of the decision support study (e.g. Andrews (1992); Andrews and Govil (1995) ; Xie and Kuby (1997); Yokohama (1997)). Similarly, this study considers that findings from trade-offs analysis are necessary for decision-makers to debate and negotiate on energy policies.

As a result, the different steps carried out in this decision support study are shown in Figure 2.2. First, electricity mix scenarios for France's 2025 generation system were built. Then, potential criteria of decision and indicator were selected leading to a sustainability assessment of the scenarios through the application of both economic indicators and socio-environmental indicators. Finally, a trade-offs analysis divided in three scale levels from overall trade-offs to trade-off inside each category and detailed trade-offs was conducted. Thus, potential scenarios' conflicts between economic and socio-environmental aspects were analyzed. The materials and method part is organized according to the same scheme.

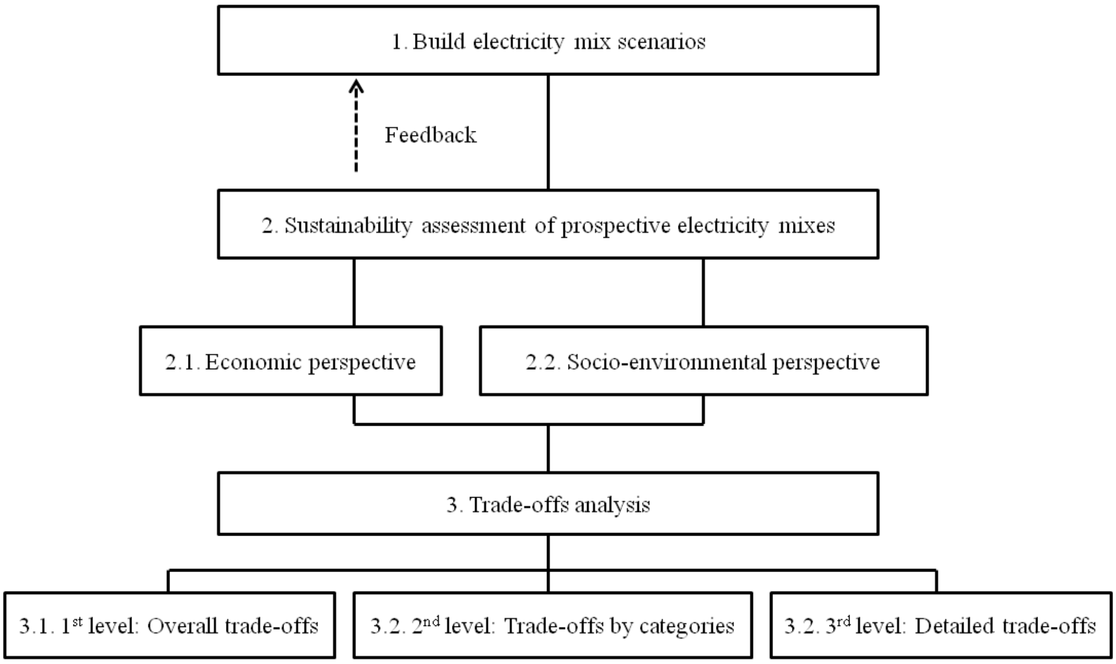

Fig. 2.2: Multi-Criteria Analysis framework in this research

2.2 Scenarios elaboration

In this study, four electricity mix scenarios were elaborated to represent four different strategies that were identified based on the categorization of the 26 scenarios in the (Percebois, 2012), the government-ordered decision support study (Figure 2.3). The first category, life extension of historical nuclear will be considered as the Business-As-Usual (BAU) scenario. The second category, a slow transition (SLO) to less nuclear power and an acceleration of the commissioning of 3rd generation of nuclear reactors will be represented as an alternative scenario. As for 50% nuclear energy scenarios in 2025, none were studied in Energies 2050 but two phase-out strategies by 2050 were studied: High renewable energies share and high fossil fuels share. As short term manifestation of those two strategies, two direction of nuclear energy share reduction to 50% by 2025 were analyzed: 50% nuclear with High RE (HRE) and the 50% nuclear with High FF (HFF). In order to ensure their comparability, the four electricity mix scenarios were built on a number of common assumptions such as electricity consumption and technology expansion forecast. Table 2.1 summarizes the different strategies as well as the common and individual assumptions made to build the four final electricity mix scenarios.

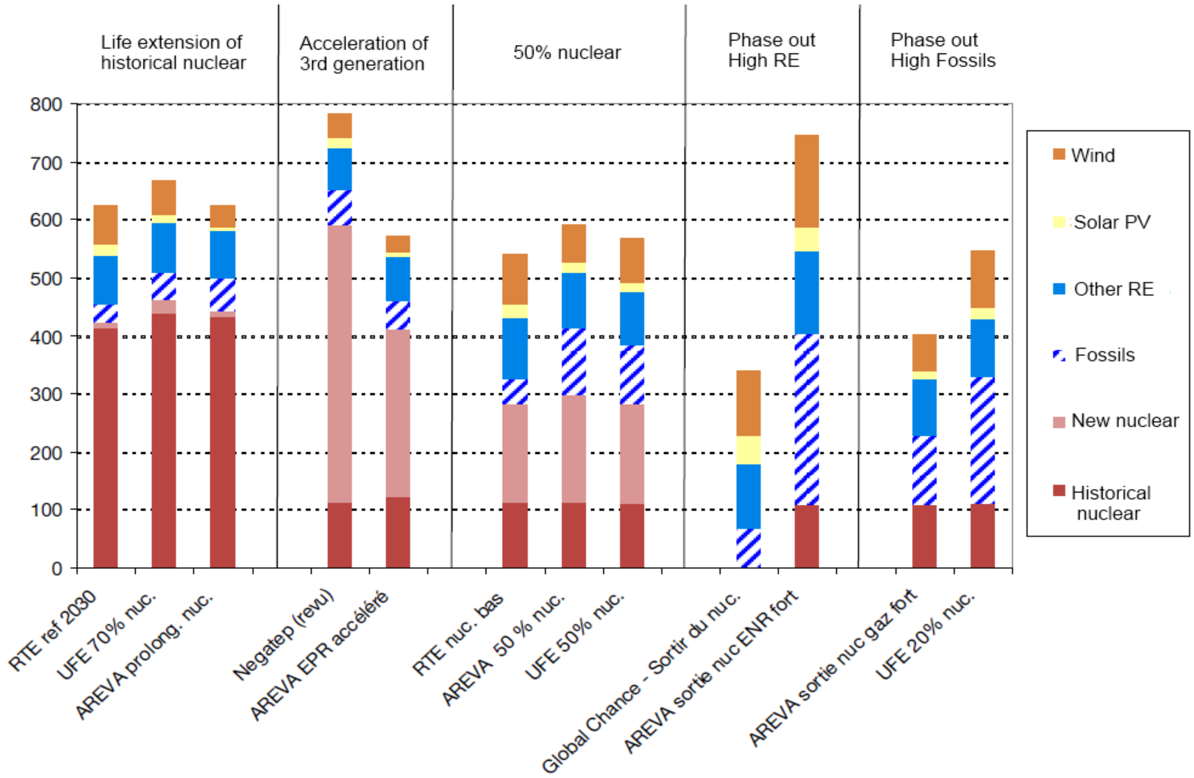

Fig. 2.3: Categorization of scenario in (Percebois, 2012)

Tab. 2.1: Main hypothesis of the four scenarios built

Scenarios	**BAU**	**SLO**	**HRE**	**HFF**
Strategy represented	*No transition* strategy: Life extension of historical nuclear power plants	*Slow reduction of nuclear share* (50% 2050, 30% 2100) and transition to G3 nuclear reactors	Transition to 50% nuclear along with a *High expansion of RE* technologies	Transition to 50% nuclear along with a *High expansion of FF* technologies
Demand-side assumption	RTE 2025 linear approximation *with* exports	RTE 2025 linear approximation *with* exports	RTE 2025 linear approximation *without* exports	RTE 2025 linear approximation *without* exports
Nuclear energy share	Life extension of NPP to 50 years	OPECST Hypothesis (Birraux et al., 2011)	50% 2025	50% 2025
Inspiration	RTE Median Scenario, UFE 70% (RTE, 2012; UFE, 2011)	RTE Median Scenario (RTE, 2012)	RTE New Mix (RTE, 2012)	UFE 50% (UFE, 2011)
Technology expansion forecast	Based on RTE reports (RTE, 2012)	Based on RTE reports (RTE, 2012)	Based on RTE reports (RTE, 2012)	Based on RTE reports (RTE, 2012)

2.2.1 Common assumptions from the demand-side

A number of common assumptions were made to provide a basis for scenario building while ensuring their comparability. Demand-side requirements, that is to say, the annual electricity demand and the daily-peak electricity demand is the main assumption scenarios are based on. Those information were collected from *Réseau de Transport d'Électricité* (RTE, 2012), the electricity transmission system operator of France [1]. Annual electricity consumption in 2025 was obtained through a linear approximation based on data for 2020 and 2030. It results that the

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[1] RTE has been appointed by the French government to produce annually a forecast overview of the balance between electricity offer and demand in France.

forecasted electricity consumption in 2025 is 531.0 TWh to be compared with a consumption of 489.5 TWh in 2012 (+8.5% over 13 years). For the nuclear-energy supported scenarios, Business-As-Usual and Generation 3 acceleration, an export hypothesis of an additional 67 TWh was used based on RTE's data (RTE, 2012). For the scenarios that involved a nuclear share decrease to 50%, the possibility of maintaining this export capacity being small, only France's electricity consumption were considered. Furthermore, RTE produced electricity mix scenarios, which include daily-peak demand considerations, and which served as basis for deciding this research's scenarios FF shares (RTE, 2012). Based on these demand-side assumptions, the four sub-mentioned scenarios were elaborated: BAU scenario, SLO transition scenario, HRE transition scenario, and HFF transition scenario.

2.2.2 Business-As-Usual (BAU) scenario

BAU scenario represents the *no transition* strategy. It is considered as the reference scenario in this research. Therefore this scenario stands for the fulfillment of the current energy policy in 2025. The lifetime of generation 2 nuclear reactor is extended from 40 years to 50 years and one generation 3 reactor, Flamanville's EPR, is put in service. As for renewable energies, their share in the electricity has been calculated based on their expansion proportion in RTE's Median Scenario 2030 (RTE, 2012). It is worth noticing that by 2025 offshore wind power enters the mix. Furthermore, usual hydropower potential is considered as fully expanded in France and very unlikely to evolve in the future, but as RE expand pumped storage hydropower plant will emerge to store electricity from renewable sources when there is no demand (RTE, 2012). As for FF participation in the mix, it has been obtained based on RTE's Median Scenario 2030 to ensure that peak demand aspects are respected (RTE, 2012). Figure 2.4 shows the Business-As-Usual 2025 electricity mix that represents the current strategy projected in 2025.

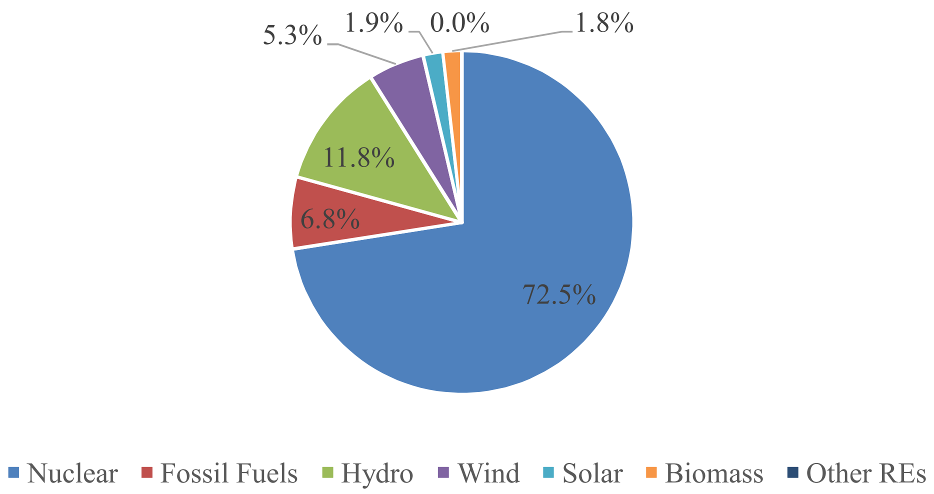

Fig. 2.4: Business-As-Usual scenario 2025 mix

2.2.3 *Slow (SLO) transition scenario*

SLO transition scenari represents the nuclear energy revival strategy. It has been promoted by the Office Parlementaire d'Évaluation des Choix Scientifiques et Technologiques (OPECST)[2] as way to strengthen the ailing French nuclear energy industry. According to (Birraux et al., 2011), "a total or partial shutdown of nuclear activity could destabilize the organization essential to its mastery, without providing any answer to the question of nuclear waste". OPECST proposes a *rational path* of the energy system, combining the respective strengths of nuclear and renewable energies. It proposes to gradually reduce the share of nuclear in electricity generation, rising from 75% today to 50-60% by 2050 and 30% by 2100. Concretely, 2025 would be in the middle of a transition from generation 2 to generation 3 nuclear reactors and this transition would occur by replacing every 3GW of generation 2 nuclear reactors by 2GW of generation 3's EPR. As for renewable energies, their share in the electricity has been calculated based on their expansion proportion in RTE's Median Scenario 2030(RTE, 2012). As OPECST hypothesis puts also more emphasis on renewable energies, their shares are slightly higher than in the BAU scenario. It is

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[2] Office for the Evaluation of Scientific and Technological Choices. It is a governmental office created "to inform Parliament of scientific and technological options in order, specifically, to make its decisions clear"

also worth noticing that by 2025 offshore wind power and tidal power enters the mix. Again, usual hydropower potential is considered as fully expanded in France and very unlikely to evolve in the future, but as renewable energies expand pumped storage hydropower plant will emerge to store electricity from renewable sources when there is no demand (RTE, 2012). As for FF participation in the mix, it has been obtained based on RTE's Median Scenario 2030 to ensure that peak demand aspects are respected (RTE, 2012). Figure 2.5 shows the SLO 2025 electricity mix that represents the OPECST hypothesis in 2025.

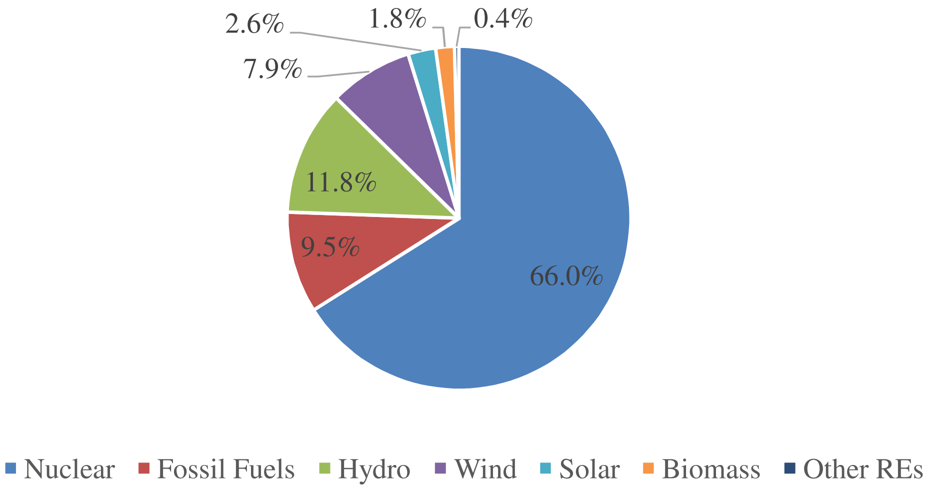

Fig. 2.5: Slow transition scenario 2025 mix

2.2.4 50% Nuclear with High Renewable Energies (HRE) transition scenario

HRE transition scenario represents the transition from nuclear powered mix to a renewable energy powered mix. It is supported by green political party as well as by an increasing share of the population [3] and by, of course, renewable energy companies. The lifetime of generation 2 nuclear reactors is not extended above 40 years meaning that the installed capacity of nuclear power would drop to 40GW in 2025. As for generation 3 reactors, the currently being built Flamanville's EPR would be the only one put in service. The share of renewable energies in the

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[3] According to an Ipsos poll, 9 french people over 10 support the expansion of RE in France (**?**).

electricity mix has also been calculated based on their expansion proportion in RTE's New Mix Scenario 2030(RTE, 2012). By 2025 offshore wind power and tidal power enter the mix. The share of renewable energies in the electricity mix has also been calculated based on their expansion proportion in RTE's New Mix Scenario 2030. By 2025 offshore wind power and tidal power enter the mix. What's more, usual hydropower potential is considered as fully expanded in France and very unlikely to evolve in the future, but as REs expansion explode in this scenario, high capacity of pumped storage hydropower plant will be installed to store electricity from renewable sources when there is no demand (RTE, 2012). As for FF participation in the mix, it has been obtained based on RTE's New Mix Scenario 2030 to ensure that peak demand aspects are respected (RTE, 2012). Figure 2.6 shows the HRE scenario electricity mix that represents the transition to a renewable energies electricity system in 2025.

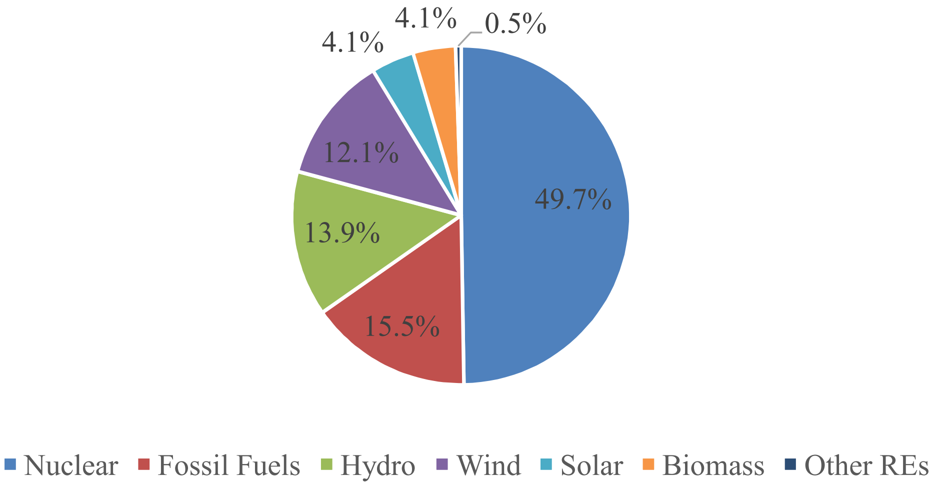


Fig. 2.6: 50% Nuclear with High Renewable Energies transition scenario 2025 mix

2.2.5 50% Nuclear with High Fossil Fuels (HFF) transition scenario

HFF transition scenario represents the transition from nuclear powered mix to a more fossil fuels oriented mix. It is presented as the only realistic 50% nuclear scenario by the nuclear industry, especially the union of utility companies, the French Union for Electricity (UFE, 2011), and it serves their nuclear revival desire as a scenario foil to repel decision-makers for initiating a decrease in the nuclear energy share. As in the 50% Nuclear with Renewable Energies scenario, the lifetime of generation 2 nuclear reactors is not extended above 40 years meaning that the installed capacity of nuclear power would drop to 40 GW in 2025. As for generation 3 reactors, the currently being built Flamanville's EPR would be the only one put in service. The share of renewable energies in the electricity mix has also been calculated based on their expansion proportion in RTE's Median Scenario (RTE, 2012). By 2025 offshore wind power and tidal power enter the mix. Once again, as usual hydropower potential is considered as fully expanded in France and very unlikely to evolve in the future, REs expansion is limited in this scenario, identical capacity of pumped storage hydropower plant as in the BAU scenario will be installed to store electricity from renewable sources when there is no demand (RTE, 2012). As for FF participation in the mix, it has been obtained based on UFE 50% 2030 scenario to ensure that peak demand aspects are respected (UFE, 2011). Figure 2.7 shows the HFF transition scenario electricity mix that represents the transition to a renewable energies electricity system in 2025.

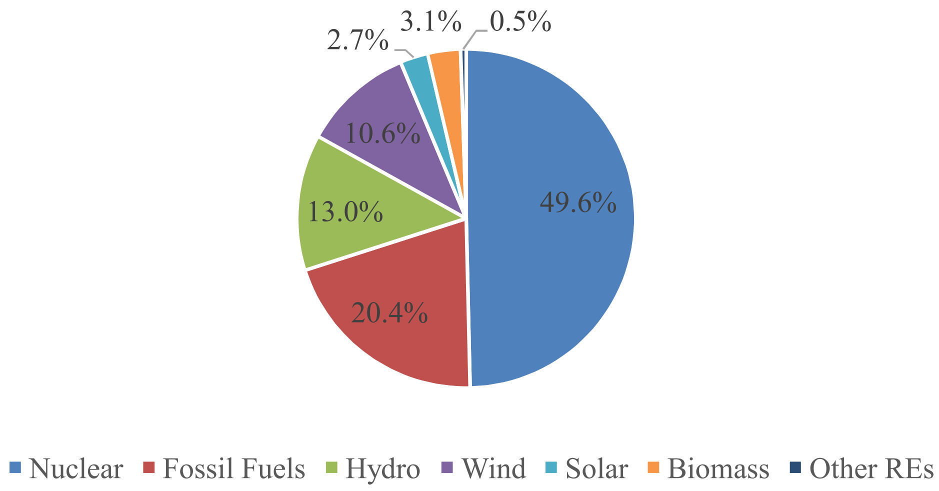


Fig. 2.7: 50% Nuclear with High Fossil Fuels transition scneario 2025 mix

2.2.6 Simplification

However, due to the lack of cost data and Life Cycle Analysis (LCA) data of minor renewable energy technologies such as thermal renewable energies (e.g., biomass, biogas and also cogeneration) and pumped storage power plant, the scenarios were *a posteriori* modified. The participation in the mix of thermal renewable energies, tidal power and cogeneration representing less than 2.9% for the BAU scenario, less than 3.4% for the SLO scenario, less than 5.8% for HRE, and less than 4.9% for the HFF scenario, their participation were neglected. For the mix production to meet the demand, other renewable energies shares were proportionally adjusted. As for the pumped storage hydropower it was in the rest of the study assimilated to an average French hydropower plant. The simplified production electricity mix scenarios are show on Figure 2.8.

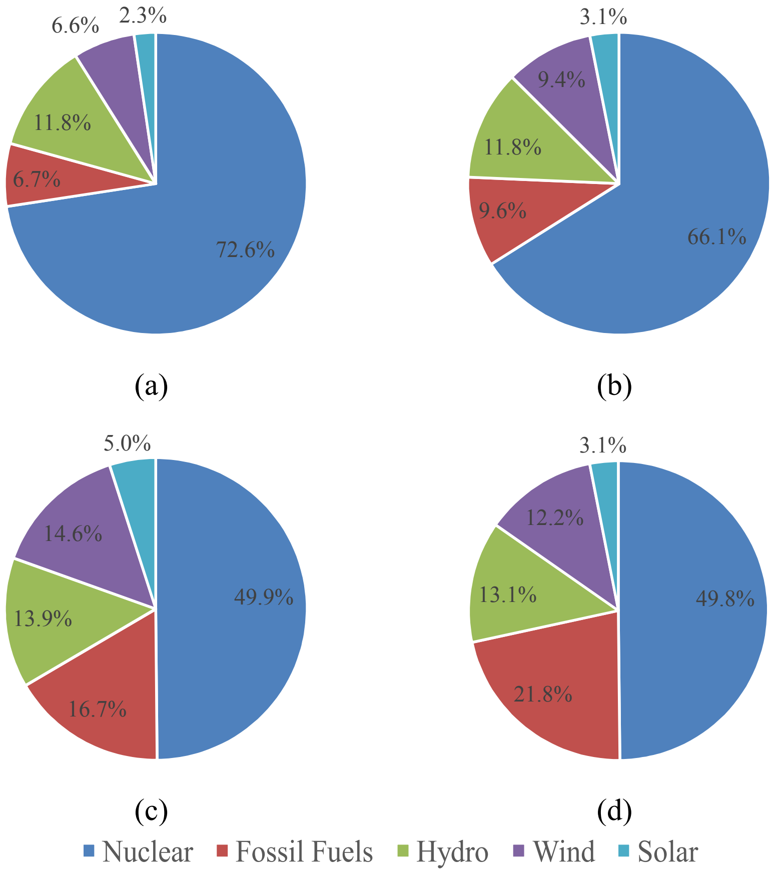
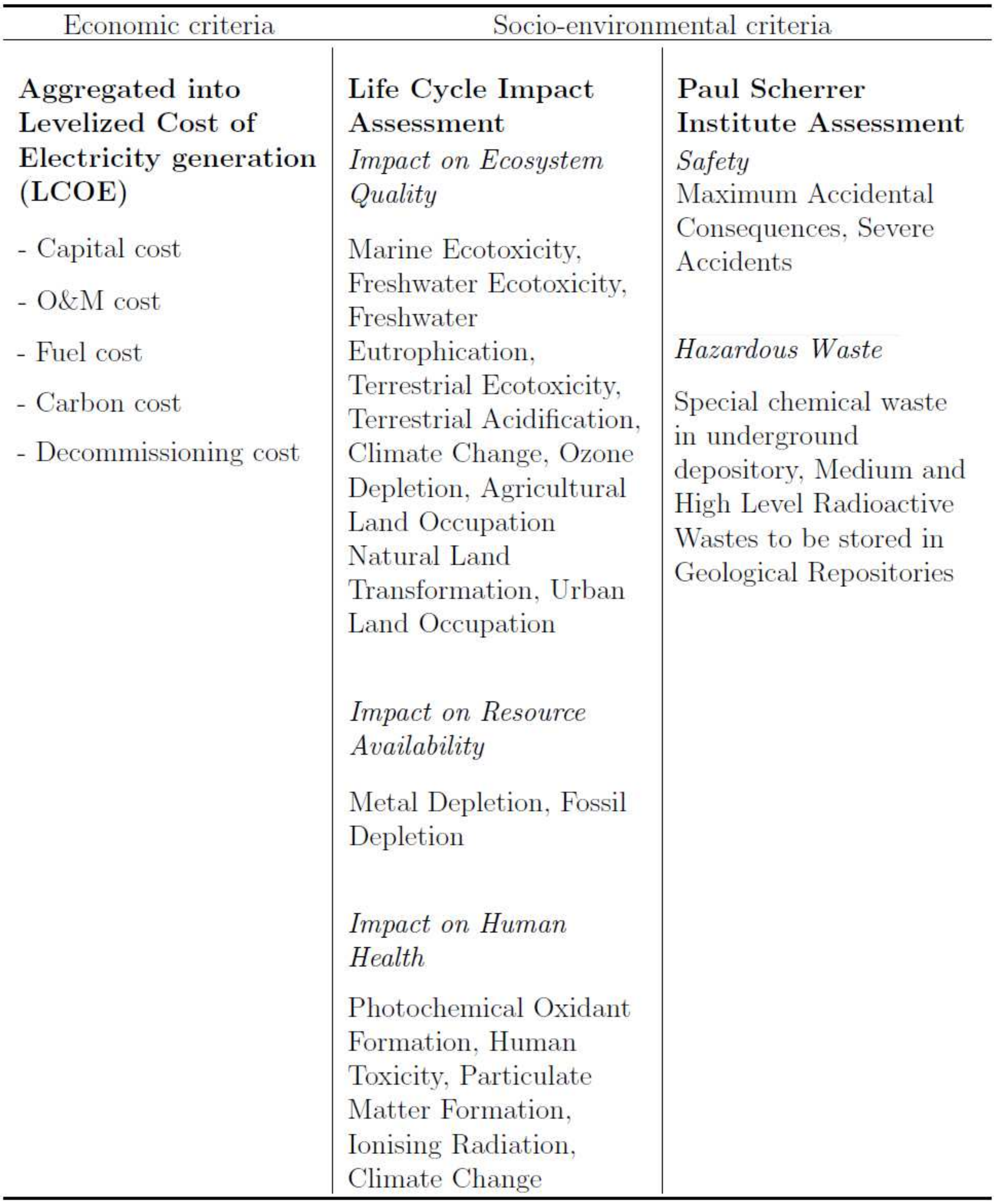


Fig. 2.8: Simplified electricity mix scenarios
(a) Initial Business-As-Usual scenario, (b) Simplified Slow transition scenario, (c) HRE transition scenario, (d) HFF transition scenario

2.3 Assessment method, indicators, and data collection

Tab. 2.2: Criteria and Indicators applied in this research



Economic criteria	Socio-environmental criteria	
Aggregated into Levelized Cost of Electricity generation (LCOE)	**Life Cycle Impact Assessment**	**Paul Scherrer Institute Assessment**
- Capital cost - O&M cost - Fuel cost - Carbon cost - Decommissioning cost	*Impact on Ecosystem Quality* Marine Ecotoxicity, Freshwater Ecotoxicity, Freshwater Eutrophication, Terrestrial Ecotoxicity, Terrestrial Acidification, Climate Change, Ozone Depletion, Agricultural Land Occupation Natural Land Transformation, Urban Land Occupation	*Safety* Maximum Accidental Consequences, Severe Accidents
	Impact on Resource Availability Metal Depletion, Fossil Depletion	*Hazardous Waste* Special chemical waste in underground depository, Medium and High Level Radioactive Wastes to be stored in Geological Repositories
	Impact on Human Health Photochemical Oxidant Formation, Human Toxicity, Particulate Matter Formation, Ionising Radiation, Climate Change	

In order to evaluate the elaborated scenarios, two types of assessment were conducted, an economic assessment and a socio-environmental assessment. In the economic assessment, cost of generating electricity by energy sources was calculated according to the Levelized Cost Of

Electricity (LCOE) method. To supplement this economic assessment, a socio-environmental assessment was carried out using two different methods. The first one gives an insight on the impact on Ecosystem, Health and Resource depletion based on a Life Cycle Impact Assessment (LCIA) (PSI, 2010) method. The second one uses data from the Paul Scherrer Institute (PSI) to answer concerns related to Hazardous and Radioactive Waste, and Safety of the power plants. Table 2.2 summarizes the indicators used in this multi criteria energy decision support research.

From the assessments of each of the electricity generation technologies, assessment of each scenario was obtained through aggregation according to their share in each of the mix scenario.

2.3.1 *Economic perspective*

There seems to be a consensus on using LCOE when assessing the of energy technologies and electricity mix scenarios. The LCOE of a power plant is the ratio between the discounted Life Cycle Cost of a power plant over the discounted lifetime expected power output. It is defined as follows:

$$LCOE = \frac{\sum\limits_{i=1}^{N_c} \frac{C_i}{(1+r)^{i-N_c-1}} + \sum\limits_{i=N_c+1}^{N_c+N_o} \frac{COM_i+CF_i+CC_i}{(1+r)^{i-N_c}} + \sum\limits_{i=N_c+N_o+1}^{N_c+N_o+N_d} \frac{CD_i}{(1+r)^{i-N_c}}}{\sum\limits_{i=N_c+1}^{N_c+N_o} \frac{E_i}{(1+r)^{i-N_c}}} \tag{2.1}$$

where r is defined as a discount rate, the $(C_i)_{1<i<N_c}$ are the annual Capital costs discounted during the N_c years of construction, the $(COM_i)_{N_c+1<i<N_c+N_o}$, the $(CF_i)_{N_c+1<i<N_c+N_o}$,and the $(CC_i)_{N_c+1<i<N_c+N_o}$ are respectively the annual Operation and Maintenance costs, the annual Fuel costs and the annual Carbon costs discounted during the N_o years of operation, the $(CD_i)_{N_c+N_o+1<i<N_c+N_o+N_d}$ are the annual Decommissioning costs discounted during the N_d years of decommissioning, and the $(E_i)_{N_c+1<i<N_c+N_o}$ are the annual productions of Electricity discounted during the N_o years of operation.

In 2010, the International Energy Agency (IEA), the Nuclear Energy Agency (NEA) and the Organisation for Economic Co-operation and Development (OECD) released a report gathering the following set of assumption to carry out a LCOE assessment (OECD et al., 2010).

- Construction, operation, and decommissioning time
- Contingency rate
- Construction expenditure schedule,
- Fuel and carbon costs

This study used this set of assumption to carry out LCOE calculation for every energy technology present in the electricity mix scenarios studied.

As for cost data, they are considered an industrial secret in the energy industry and as such are hardly transparent in a few reports. Moreover, costs data are rapidly outdated due to rapid variation of the costs of certain technologies. The 2010 report released by IEA, NEA and OECD gathered power plant costs based on 2008 data from OECD countries and some emerging countries as well (OECD et al., 2010). In 2012, the International renewable Energy Agency (IRENA) released a report including cost data in European OECD countries (IRENA, 2012). The case of nuclear power is more complicated as cost data communication is left to the will of the nuclear industry, detailed costs were not available. However, in June 2011, the French accountancy Court, the Cours des Comptes (CdC), was asked by the prime minister to lead an inquiry on this non-transparency that resulted in the release of a report of overall generation costs for the current nuclear power plant park and the generation 3's EPR in January 2012 (CdC, 2012). Nevertheless, in December 2012, AREVA announced that the capital cost of the Flamanville's EPR was raised from 6bn euros to 8.8 bn euros (LeMonde.fr, 2012). In order to take those recent evolutions in consideration, the additional capital cost was discounted and added to the French Accountancy Court estimated LCOE. Furthermore, the cost evolution is different for each technology as renewable energy costs decrease with experience whereas cost of nuclear power plants increases. This aspect being essential when talking about transition towards less nuclear energy, whenever possible, most up-to-data data were collected. Table 2.3 shows the data sources used for each type of power plants.

Tab. 2.3: Cost data sources for each power plant

Power plant	Source
Hydropower	(IRENA, 2012a)
Onshore wind	(IRENA, 2012c)
Offshore wind	(IRENA, 2012c)
Photovoltaic	(IRENA, 2012b)
Coal	(OECD et al., 2010)
Combined Cycle Gas	(OECD et al., 2010)
Nuclear G3	(CdC, 2012)
Nuclear G2	(CdC, 2012)

In order to calculate an estimation of the electricity production, capacity factors were taken into account. Capacity factors are defined as the ratio of its actual output over a period of time, to its potential output if it were possible to operate it at full during this same period of time. Those data were, whenever possible, taken from statistical sources such as RTE data on annual electricity generation by sources. When it was not possible to find any statistical data, assumptions from the Organisation for Economic Co-operation and Development et al. (2010) were used. Table 2.4 shows the capacity factors and data sources for each energy technology.

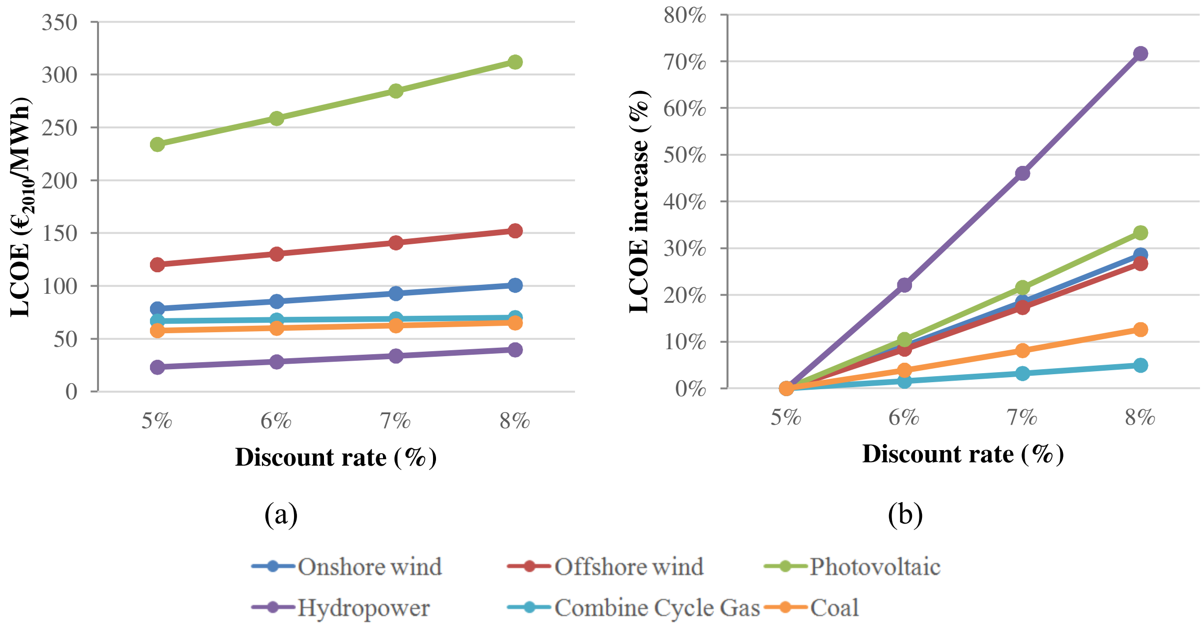
Tab. 2.4: Capacity factor data and sources

Power plant	Capacity factor	Source
Onshore wind	20.00%	(RTE, 2012)
Offshore wind	30.00%	(RTE, 2012)
PV	12.50%	(RTE, 2012)
Nuclear G3	90.00%	(OECD et al., 2010)
Nuclear G2	76.00%	(RTE, 2012)
Coal	55.00%	(RTE, 2012)
Combined Cycle Gas	60.00%	(RTE, 2012)
Hydropower	31.50%	(RTE, 2012)

As for the choice of a proper discount rate, there is no consensus even though it has seemingly a significant impact on the LCOE. The discount rate, defined as a “coefficient to convert the future to the present”, enables the utility companies to provision money today for their future expenses (CdC, 2012). As mentioned by the CdC, several discount rates have been used to calculate LCOE in the past (CdC, 2012). French operators used a 5% discount rate based on the following assumptions:

- a long-term inflation rate of 2%, -
- 3% in true value, implying repetition of past performances in the bond and stock markets.

Those assumptions are considered bullish by the CdC, which does neither validate previously used discount rate (7.8%, 8.4% in previous reports) nor provide any systematic value (CdC, 2012).



(a)

(b)

Fig. 2.9: Sensitivity analysis of the impact of discount rate on LCOE
(a) Discount rate impact on LCOE, (b) LCOE increase with discount rate

Consequently, a sensitivity analysis of the impact of discount rate on LCOE was realized (Fig. 2.9). The results show a high sensitivity of the discount rate. LCOE increases from +8€$_{2010}$/MWh for coal power plant to +75€$_{2010}$/MWh for photovoltaic plants for DRs from 5% to 8%. Besides, from 5% to 8%, the LCOE of technologies increase from 5% for gas power plant to 72% for hydropower plant. The LCOE increase is, seemingly, directly linked to the share of capital cost in the total lifetime costs of technologies. This can be observed on the LCOE equation 2.3.1 as well. The discounting has higher influence on capital costs than other costs as the exponent of the discount factor is smaller on the capital discounted cost terms. As a result, discount rates ranging from 5% to 8% were used in this research in order to take this uncertainty into consideration.

2.3.2 Socio-environmental perspective

In order to model the socio-environmental impacts of scenarios, two types of analysis were considered. First a LCIA was conducted to gather impacts related to ecosystems, resources availability and human health. Secondly, statistical data as well as LCA data were used to analyze the impact of accident and hazardous wastes.

Life Cycle Impact Assessment (LCIA)

In order to analyze the socio-environmental impact of the 2025 electricity mix, LCA was supplemented with the ReCiPe 2008 Impact Assessment method (Goedkoop et al., 2009). LCA is is quantitative assessment of the life cycle of products or activities. It provides an inventory, that is to say, a very long list of emissions, consumed resources and wastes generated at each step of the life cycle. To analyze the impact of this inventory, a Life Cycle Impact Assessment was used. It categorizes the inventory data into indicators that evaluate the potential impacts of this inventory. In this research, the ReCiPe 2008 LCIA method was used because it is the latest development of a long-lasting family of LCIA method focusing on European conditions. Figure 2.10 presents the ReCiPe 2008 framework and impact categories. On one hand, the first set of indicators, the midpoint indicators, expresses the potential impacts according to 18 midpoint impact categories, which are accurate but relatively difficult to interpret for decision-makers. On the other hand, the endpoint set of indicators is an easy-to-understand set design for decision-makers that gathers the midpoint indicators into three global indicators that represents the relative severity of three main environmental impact categories:

- Damage to human health
- Damage to ecosystem quality
- Damage to resource availability

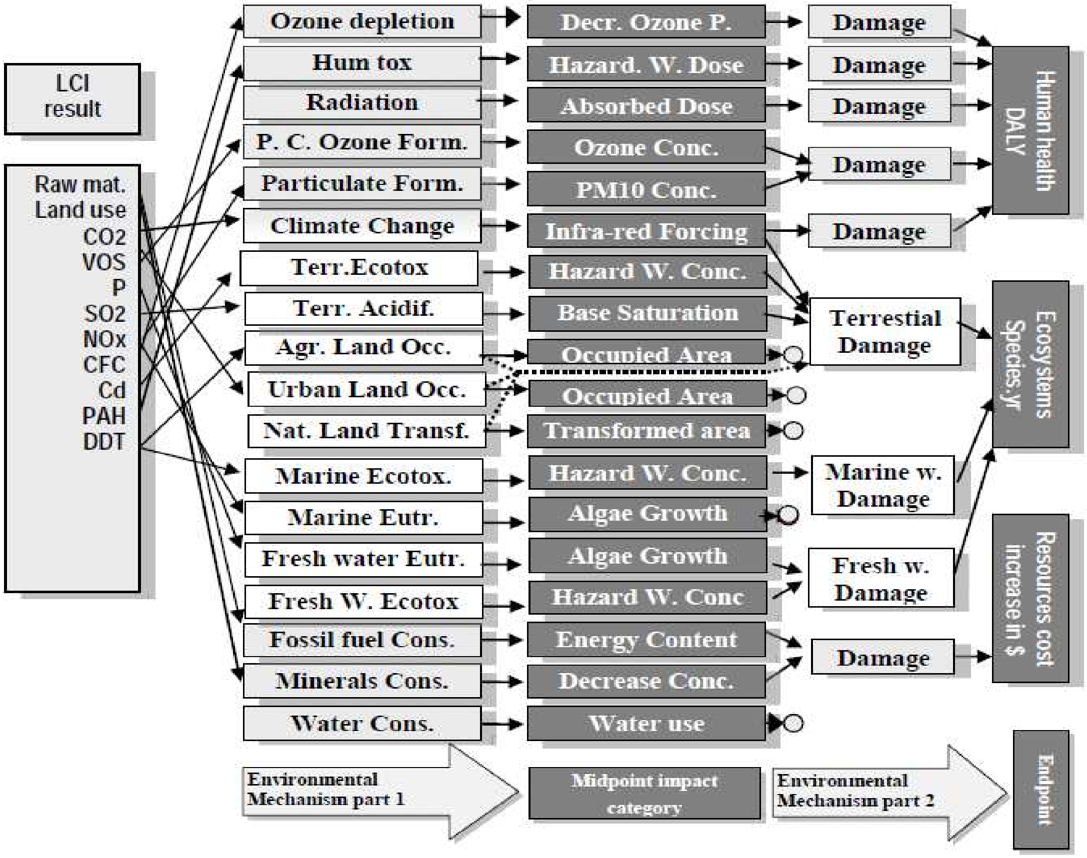


Fig. 2.10: ReCiPe 2008 set of indicators (Goedkoop et al., 2009)

In this research, endpoint and midpoint assessments have been combined to have both an optimal accuracy and ease of interpretation. As for the LCA data, representative dataset of every electricity generation technology involved in the electricity mix scenarios have been collected in the ecoinvent [4] database, and selected to match the French location, if not European-wide available data were chosen.

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[4] The ecoinvent database http://www.ecoinvent.ch/ is the world leading LCA database and is specialized in energy supply systems. To analyze the LCA data, openLCA was used http://www.openlca.org/

Paul Scherrer Institute Assessment

As presented in the introduction part, Paul Scherrer Institute (PSI) is a pioneer research institute in the assessment of energy technologies. It is especially well-known for having been granted the leadership of the European Commission project NEEDS (New Energy Externalities Development for Sustainability) and as such it has developed a wide range of indicators of socio-environmental impacts. PSI assessment indicators and data were used to broaden the socio-environmental assessment and include concerns related to nuclear waste and safety. To supplement the impact on ecosystem, resources and human health calculated using LCIA, two categories from PSI's set of criteria were taken into account in this research:

- Hazardous wastes (LCA)
  - Special chemical wastes stored in underground depositories
  - Medium and high level radioactive wastes to be stored in geological repositories
- Accident (ENSAD database[5])
  - Maximum consequences of accident
  - Death from severe accidents

LCA and ENSAD data for each energy technology was collected in PSI publication (PSI, 2010). As a result a complete socio-environmental assessment including both LCIA and PSI indicators was conducted to analyze the electricity mix scenarios.

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[5] PSI has established Energy-related Severe Accident Database (ENSAD), a comprehensive database on severe accident, which cover all stages of energy chains for a variety of energy sources and technologies (Hirschberg et al., 2004a)

2.4 Trade-off Analysis

So as to present decision-makers with all the potential compromises hidden in the choice an electricity mix alternative, trade-offs analysis of scenario was conducted. Trade-off plots have long been used to aid understanding of the environmental dimensions of energy choices (Ferrell, 1978). In this research, two type of trade-offs curves will be studied.

2.4.1 1st and 2nd level analysis

In the 1st and 2nd level of analysis, general trade-offs from the perspective of categories of indicators are looked at using *spider web diagram* (Hobbs and Meier, 2000). A spider-web diagram is meant to make the multi-dimensional aspect of trade-offs easy to understand for decision-makers, (Fig. 2.11). In this diagram, each branch represent different attributes which are scaled so that the worst impact value of each attribute is at the bottom of the bar and the best impact is at the top of the branch.

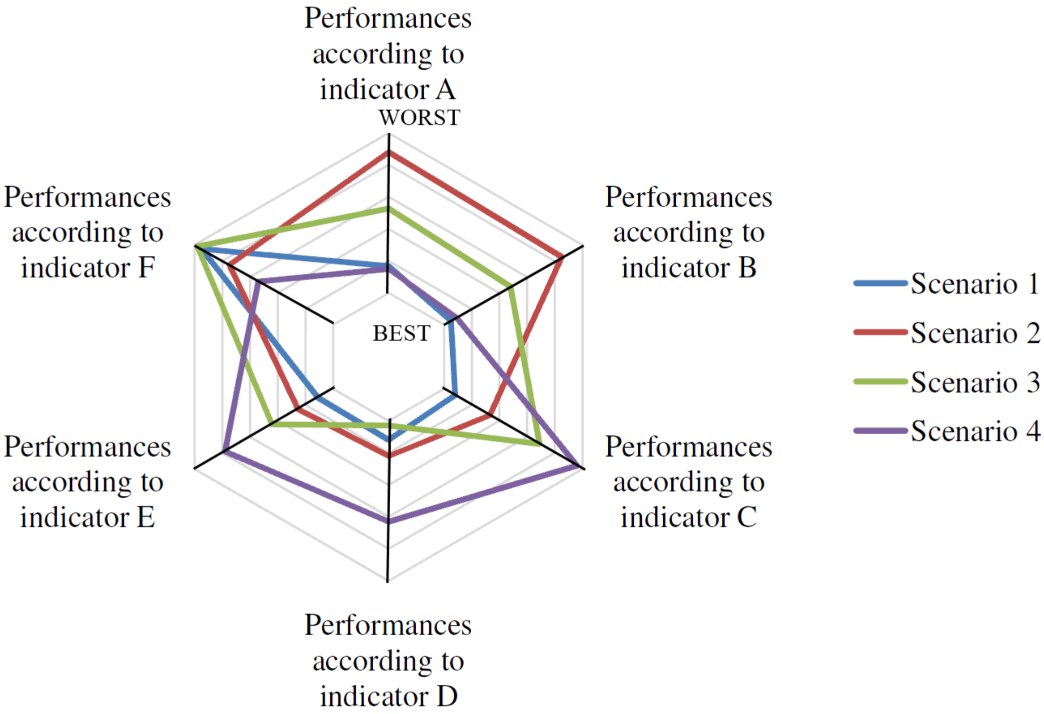


Fig. 2.11: Example of spider web diagram

2.4.2 3rd level analysis

In the 3rd level analysis, detailed trade-offs are looked at using traditional bi-dimensional trade-off graphs. The analysis process of those trade-off curves are presented Figure 2.12. Each number represents an alternative and the graph is divided into four quadrants defined by the performance of the reference alternative R. Alternatives that are in the quadrant I perform worse according to the two indicators, X and Y and therefore represent a *lose-lose* case. On the other hand, alternatives in quadrant III performs better than the reference alternative and are *win-win* options. When analysing trade-offs, apart from win-win and lose-lose cases, trade-offs trends are looked at . Trade-offs trends represent an organisation of scenario's trade-offs. Trade-offs trends are easily observable on bi-dimensional trade-off curves. On Figure 2.12, performances of scenarios 5, 7, R, 8, 9 are organized according the following trade-off trend: the best impact the scenario have on indicator Y, the worse theur impact on indicator X becomes. Such an organizations of scenarios' performances makes the decision easier to grasp.

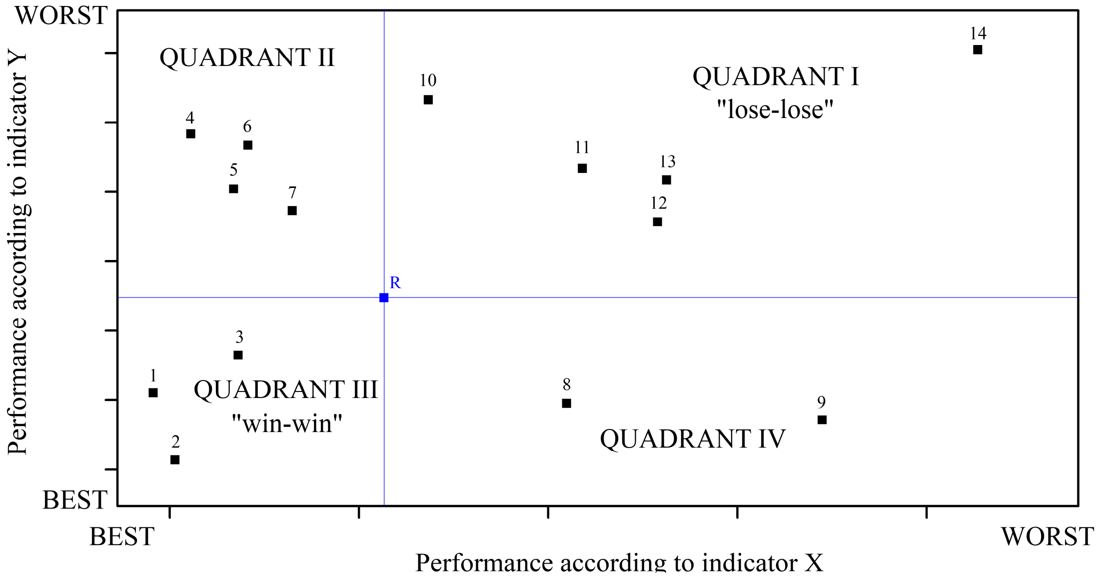


Fig. 2.12: Two dimensions trade-off plot (Hobbs and Meier, 2000)

In this study, the reference alternative will be set as the Business-As-Usual scenario, so we can analyze the meaning of an electricity transition through the three transition scenarios (SLO, HRE, and HFF). Furthermore, the assessments previously conducted include 22 indicators and therefore, 253 trade-off curves should be plotted. In order to avoid potentially confusing information pollution and because the current decision-making process is focused on cost analysis, it was decided to look only at the cost of scenarios versus their socio-environmental impacts. As a result, multi-dimensional trade-off plots supplemented by traditional trade-offs graphs were used to identify the main trade-offs implied by each scenario and display it to decision-makers.

3

RESULTS

In this part, scenario performances and trade-offs analytical results are introduced following the logic of scales: from trade-offs among overall performances to detailed trade-offs among indicator performances. In the 1st level analytical results part, overall scenarios' performances are shown from the perspective of average category performances. Then, in the 2nd level analytical results part trade-offs inside each socio-environmental categories are presented. Finally, in the 3rd level analytical results part bi-dimensional trade-offs curves analysis of costs against socio-environmental performances expressed in percentage compared to the Business-As-Usual (BAU) scenario's, which is considered hereafter as the reference scenario.

3.1 1st level analytical results: overall scenarios' performances

Figure 3.1 presents a spider web diagram with the averaged performance of scenarios in 7 categories: cost according to a 5% discount rate, cost according to a 8% discount rate, hazardous wastes, safety, human health, resources damages and ecosystem quality. In term of cost performances, with a 5% discount assumption, the 50% nuclear High FF transition (HFF) scenario is the least expensive followed by the BAU scenario, and the 50% nuclear High RE transition (HRE), the Slow transition (SLO) scenario being the most expensive one. On the other hand, with 8% discount rate the BAU scenario becomes the least expensive one. Regarding the impacts on ecosystem quality, resources damages and human health, all scenarios shows the same range of performances according to each of the three categories. BAU scenario show the best performances, then HRE scenario, followed by SLO scenario, have middle range impacts. HFF scenario acknowledges the highest impacts according to those three overall indicators. In term of hazardous waste generation, HRE scenario and HFF scenario are the least impacting scenarios whereas SLO scenario shows middle range impact and BAU scenario has the worst performance. In regards to the safety overall indicator, again, HRE scenario and HFF scenario are the best performers. BAU scenario has a middle-range performance while SLO performs the worst. Thus, the analysis of trade-offs of overall scenarios' socio-environmental performances results gave general trends on their performances according to each category of evaluation.

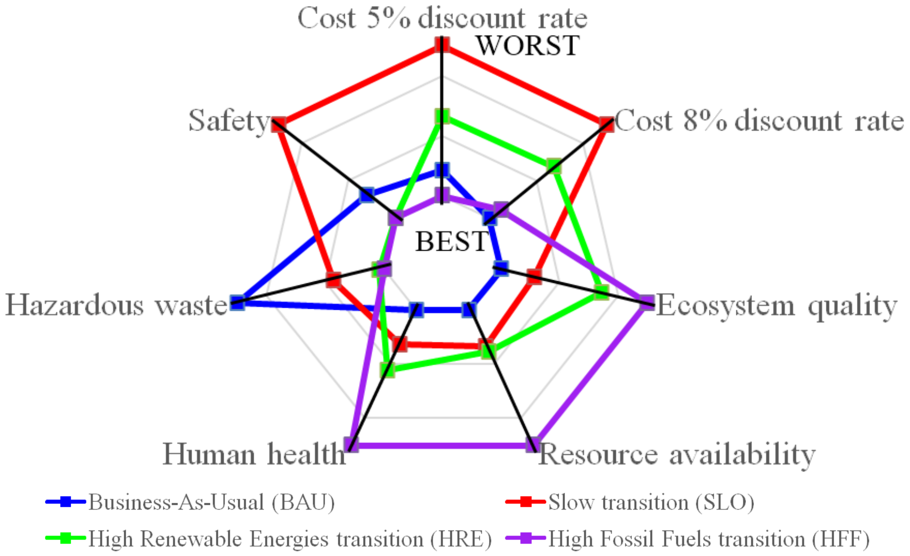
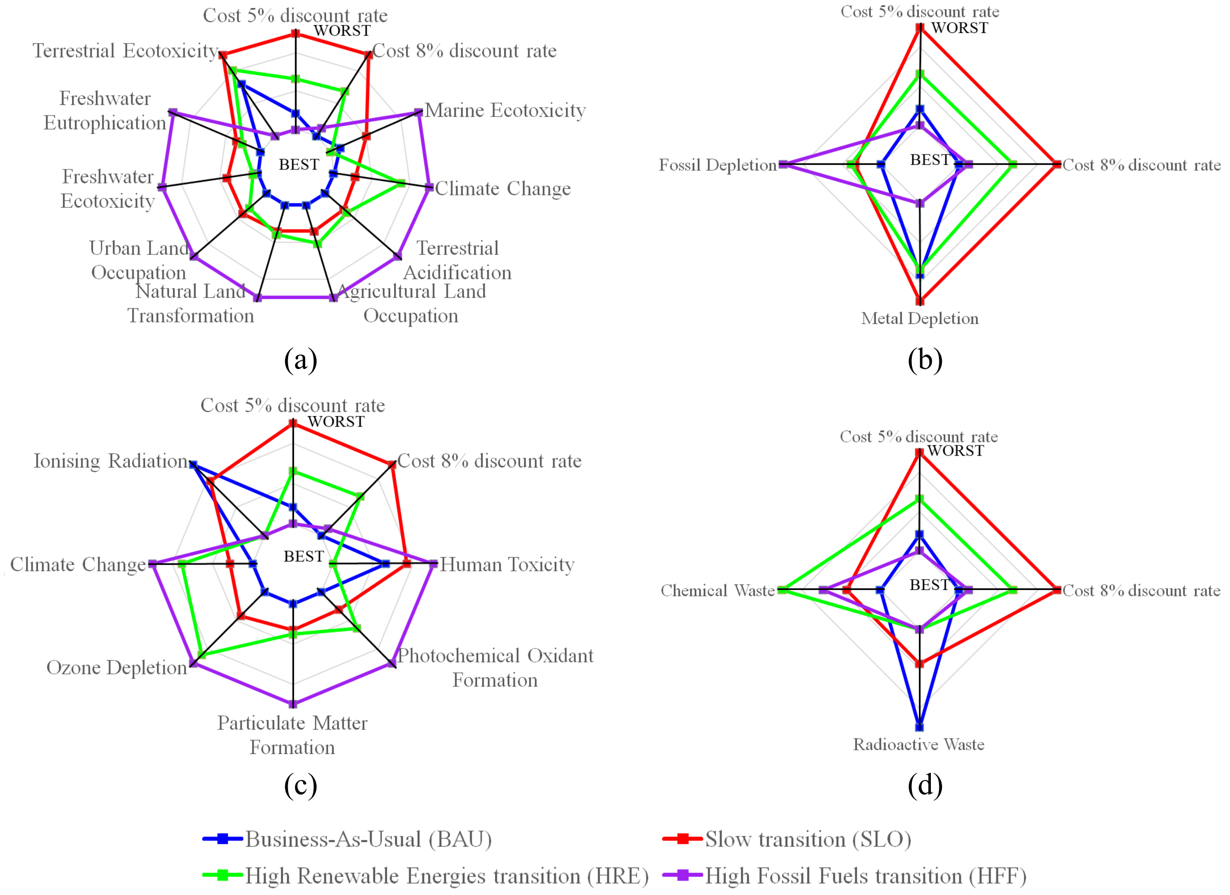


Fig. 3.1: Overall scenarios' performance

3.2 2nd level analytical results: subcategory scenarios' performances

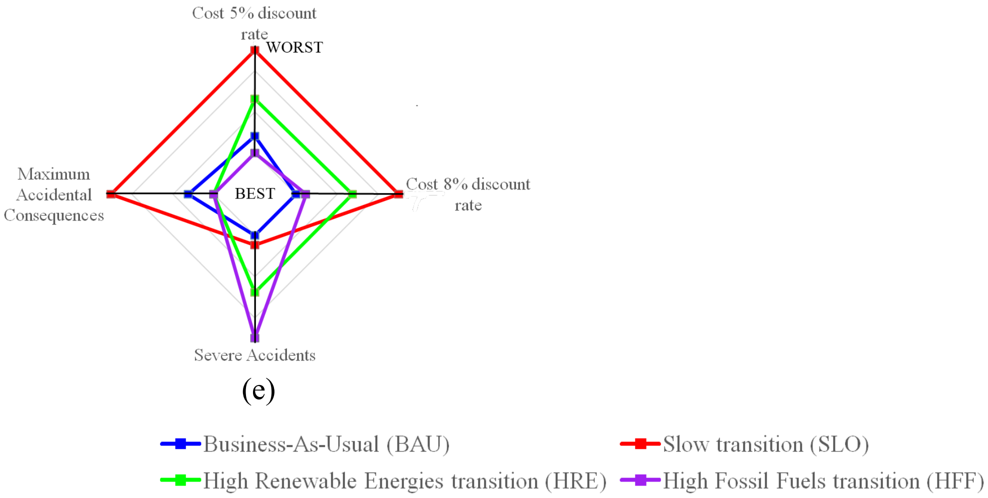
Figures 3.2 and 3.3 shows 5 spider web diagrams presenting the scenarios performances around the 5 socio-environmental categories analyzed. Figure 3.2 (a) presents the performance of scenarios with regard to subcategories of ecosystem quality. Compared to transition scenarios, the BAU scenario shows relatively good performances. Among the 9 subcategories, BAU scenario only performs relatively worse in terms of terrestrial ecotoxity compared to other transition scenarios. Besides, HFF scenario appears to perform the worst as among 9 subcategories, it only shows good performances in terms of terrestrial ecotoxicy. SLO and HRE scenarios generally seem to exert middle range impacts on ecosystem. However, SLO shows the worst performance according to the terrestrial ecotoxicity indicators and HRE scenario performs relatively bad on the climate change and terrestrial ecotoxicity aspects. Figure 3.2 (b) presents the performance of scenarios with regard to subcategories of resources availability. HFF scenario shows the best performances according to the metal depletion indicators, but the worst according to fossil fuels depletion. BAU scenario and HRE scenario have middle-range performances on metal depletion. Nevertheless, BAU scenario performs the best in fossil depletion while HRE scenario has middle range performances according to this indicator. SLO scenario performs the worst in metal depletion and exert middle-range performances on fossil depletion. The performances of scenarios according to the subcategory indicators of human health impact are shown in Figure 3.3 (c). HFF scenario has the worst performances according to 5 of the 6 human health indicators, showing the best performances in the ionizing radiation subcategory. BAU scenario performs the best according to 4 indicators but shows middle-range impact on human toxicity and the worst impact on ionizing radiation. HRE scenario basically has middle-range performance on human health indicators except for ozone depletion where it performs the worst and climate change where it is close to the worst. However it shows the best performances according to the human toxicity indicator. SLO scenario has middle-range performances on all indicators except ionizing radiation where it is among the worst. As for the hazardous waste indicators, scenarios performances are shown on Figure 3.3 (d). BAU scenario shows the best performances on chemical waste generated, but the worst on the generation radioactive waste. HFF scenario and HRE scenario performs the best according to the radioactive waste indicator, but HRE scenario followed by HFF scenario are the worst performers in terms of chemical waste. SLO scenario shows mid-range impacts on both waste criteria. Finally Figure 3.3 (e) shows scenario’s performances according to the safety category. Severe accident impacts are the highest for HFF scenario but it performs the best according to the maximum accidental consequences subcategory. On the contrary, SLO scenario performs the worst on maximum accidental consequences but is among the best performers in term of sever accidents. BAU scenario shows the best performances in term of severe accidents. HRE scenario has mid-range performances in severe accidents and performs the best in maximum accidental consequences with HFF scenario. Consequently, inside each socio-environmental category, there are numerous variation in the ranking of scenarios according to each indicators.



(a) (b)

(c) (d)

Fig. 3.2: Scenario's performances on socio-environmental subcategory indicators
(a) ecosystem quality, (b) resource availability, (c) human health, (d) hazardous waste



(e)

Fig. 3.3: Scenario's performance on socio-environmental subcategory indicators (continued) (e) safety

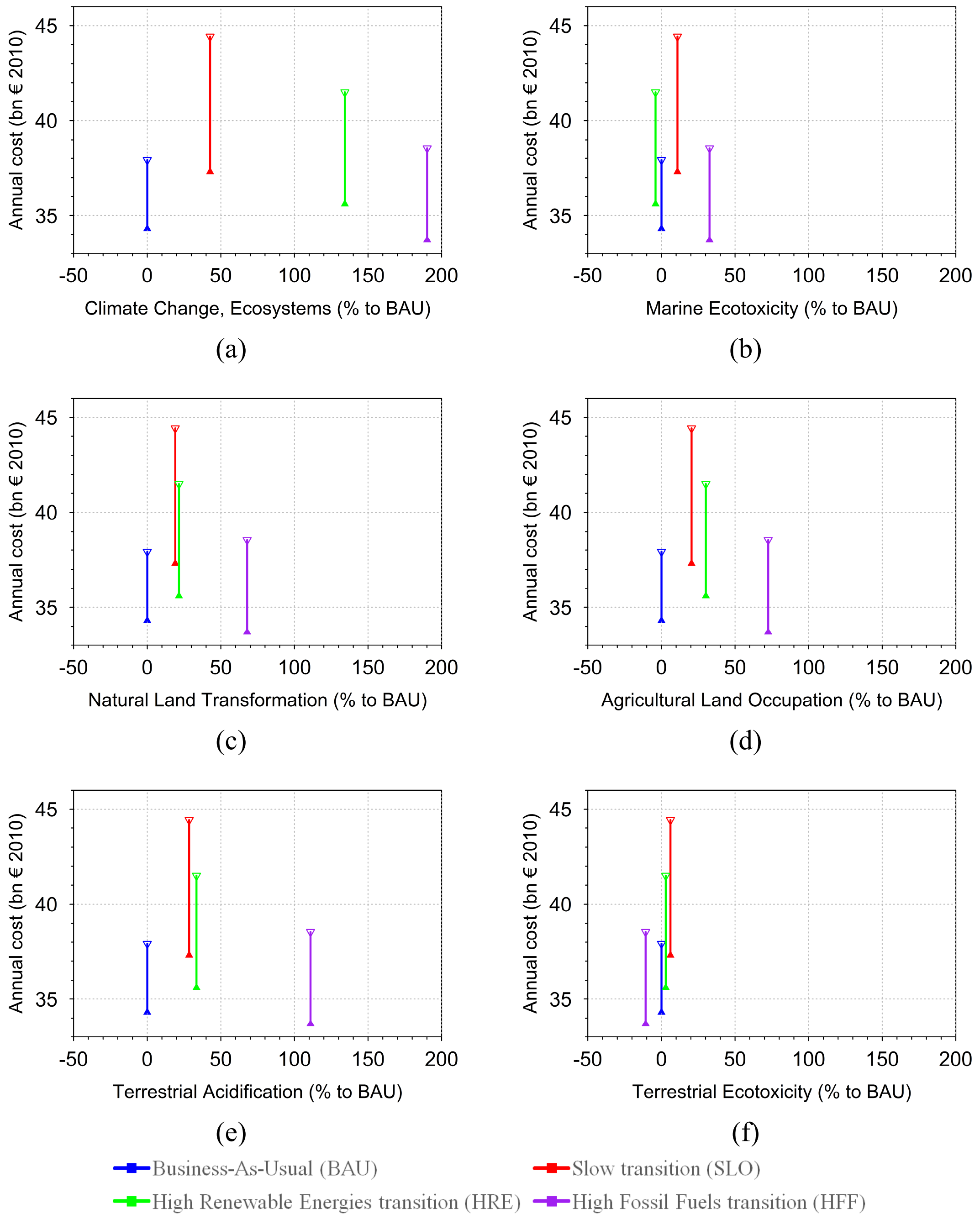
3.3 3rd level analytical results: trade-offs of costs against socio-environmental impacts

Bi-dimensional trade-offs analysis was conducted taking into account socio-environmental impact differences between transition scenario and the reference scenario, the BAU scenario, against the costs. In this section, the bi-dimensional trade-offs graphs are shown according to each indicators and organized category by category. Trade-offs curves are analyzed in the perspective of trade-off trends of transition scenario and their situation compared to the reference scenario.

In term of costs, a change of the discount rate from 5% to 8% lead to a change in the scenario costs ranking. BAU scenario, least expensive at 5% becomes 2nd least expensive in favour of HFF scenario. The cost difference between 5% discount rate and 8% discount rate is 3.6 bn euros 2010 (+10.5%) for the Business-As-Usual scenario (BAU), 7.1 bn euros 2010 (+19.1%) for the SLO transition scneario, 5.9 bn euros 2010 (+16.6%) for the HRE transition scenario, and 4.85bn euros 2010 (+14.4%) HFF transition scenario.

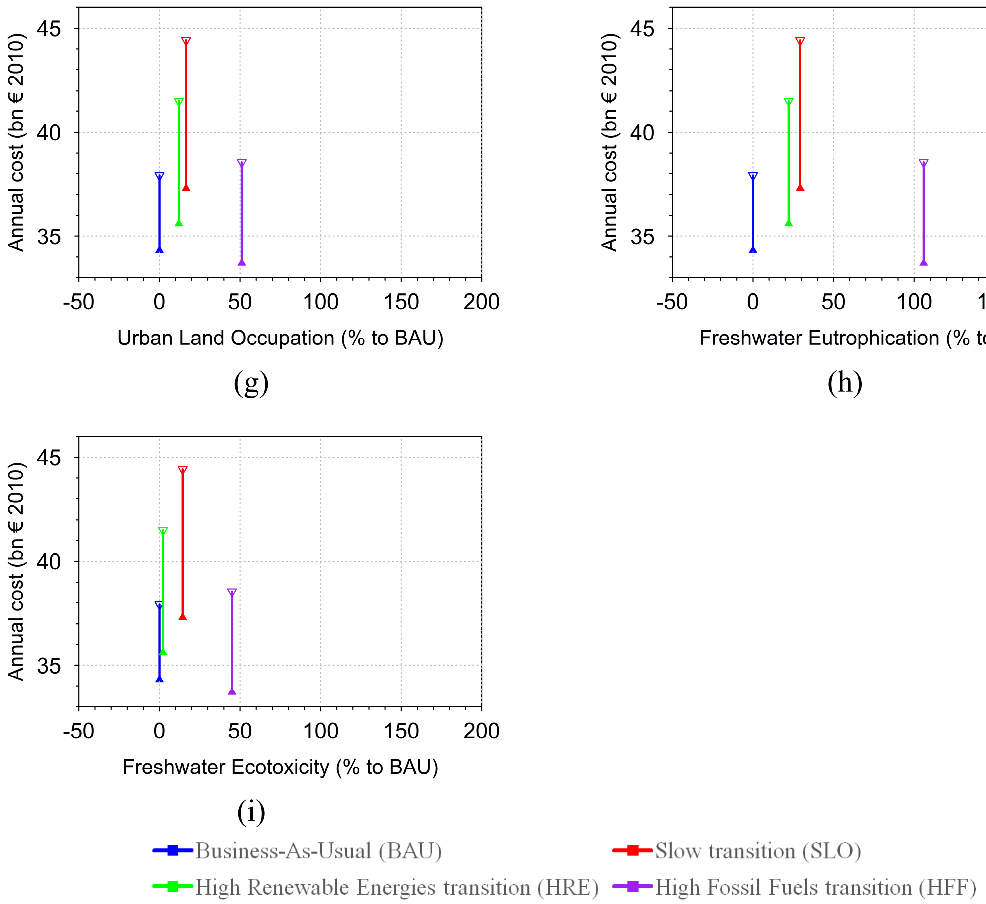
3.3.1 Trade-offs against ecosystem quality

Figures 3.4 and 3.5 show the trade-off graphs between costs and ecosystem quality impacts indicators. Transition scenario are almost never in a win-win situation compared to the reference scenario BAU scenario. Only one win-win situation can be observed for the HFF scenario in the trade-off graph of costs against terrestrial ecotoxicity. However, the transition scenarios are often in a lose-lose situation, their impact according to most ecosystem quality indicators being higher than BAU scenario along with their costs. This can be observed for all the trade-off graphs except terrestrial ecotoxicity. HFF scenario is, for a discount rate of 5%, never in any lose-lose situation, but its impact is often between 80% and 190% higher than BAU scenario's. Among the transition scenarios, two opposite trade-offs trends can be observed. The first one can be seen in the trade-offs graphs of costs against climate change, agricultural land occupation, natural land transformation, and terrestrial acidification. It seems that as costs of transition scenarios decrease, the impact according to those indicators increase. On the other hand, on trade-off graphs of costs against terrestrial ecotoxicity, costs of scenario increase along with their impact according to this indicator even though the terrestrial ecotoxicity impacts are very similar for all scenarios ranging from -10% to +10% of BAU scenario's. As a result, according to trade-offs graphs of ecosystem quality indicators against costs, transition scenarios are mostly in a lose-lose situation compared to BAU scenario. Also, a trend of trade-offs involving transition scenario's cost decrease along with ecosystem quality impacts increase has been observed.



(a) (b) (c) (d) (e) (f)

Fig. 3.4: Trade-offs of costs against ecosystem quality impacts
(a) climate change, (b) marine ecotoxicity,(c) natural land transformation, (d) agricultural land occupation(e) terrestrial acidification, (f) terrestrial ecotoxicity



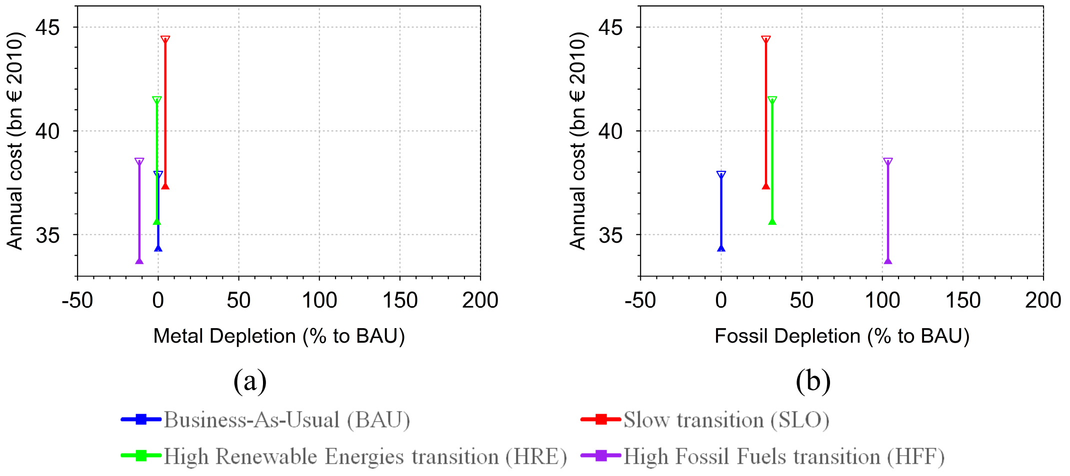
(g) (h)

(i)

Fig. 3.5: Trade-offs of costs against ecosystem quality impacts (continued)
(g) urban land occupation, (h) freshwater eutrophication, (i) freshwater ecotixicity

3.3.2 Trade-offs against resource availability

Figure 3.6 presents the trade-off graphs between costs and resource availability impacts. According to the trade-offs graphs, win-win situation compared to this reference scenario can be observed on the trade-off graphs of costs against metal depletion. Indeed, HFF scenario, assuming a 5% discount rate is less costly and has less impact on metal depletion. According to this same trade-off graph, the only scenario in a lose-lose position is the SLO scenario. Besides, according to the trade-off graph of cost against fossil depletion, transition scenarios are in a lose-lose situation as their impact are higher than BAU scenario along with their costs. For a discount rate of 5%, HFF scenario is not in any lose-lose situation, but its impact is 100% higher than BAU scenario's. Among the transition scenarios, two opposite trade-offs trends can be observed. For the trade-offs involving metal depletion, there is a negative trade-offs trends as costs of transition scenarios decrease, their impact follow. However, on trade-off graphs of costs against fossil depletion, there is a trade-offs trend: costs of scenario increase while their impact increase. Thus, a clear tendency of transition scenario being in a lose-lose situation compared to BAU scenario has been observed. Furthermore, negative trade-offs trends of costs against metal depletion and positive trade-offs trends of costs against fossil depletion were pointed out.

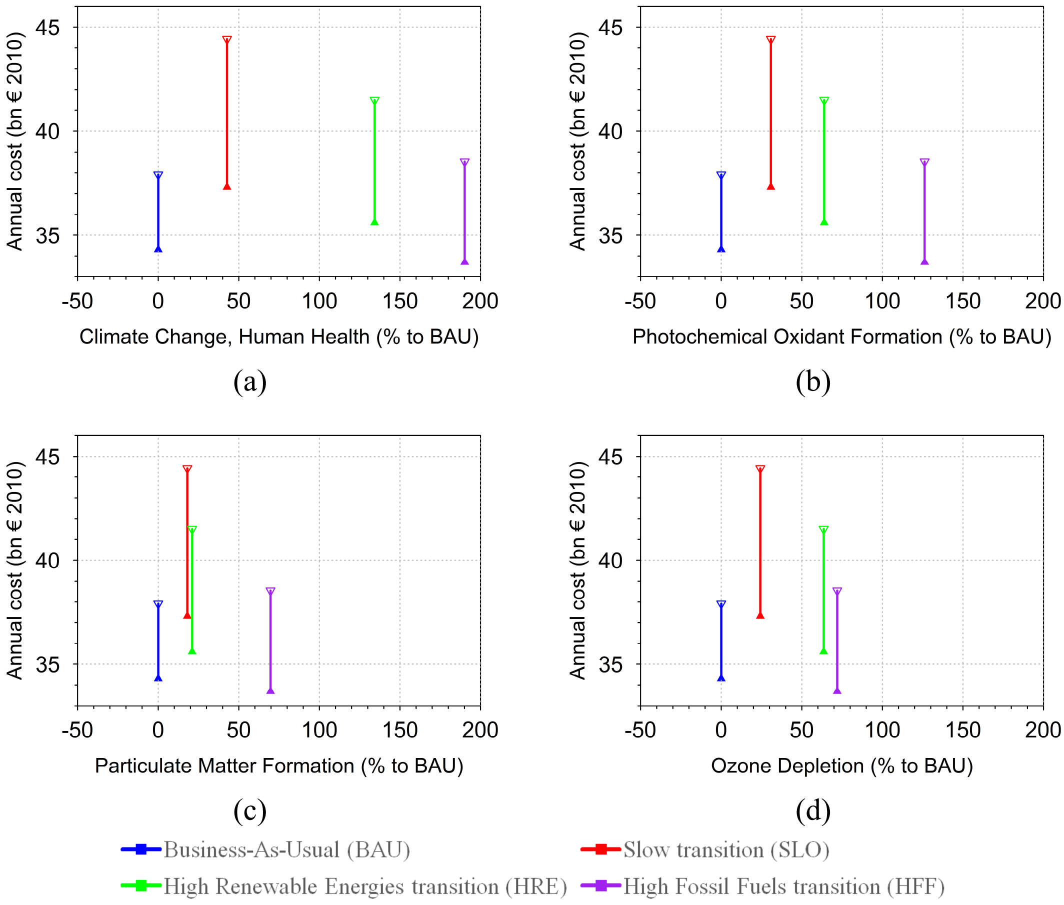


(a) (b)

Fig. 3.6: Trade-offs of costs against resource availability impacts
(a) metal depletion, (b) fossil depletion

3.3.3 *Trade-offs against human health*

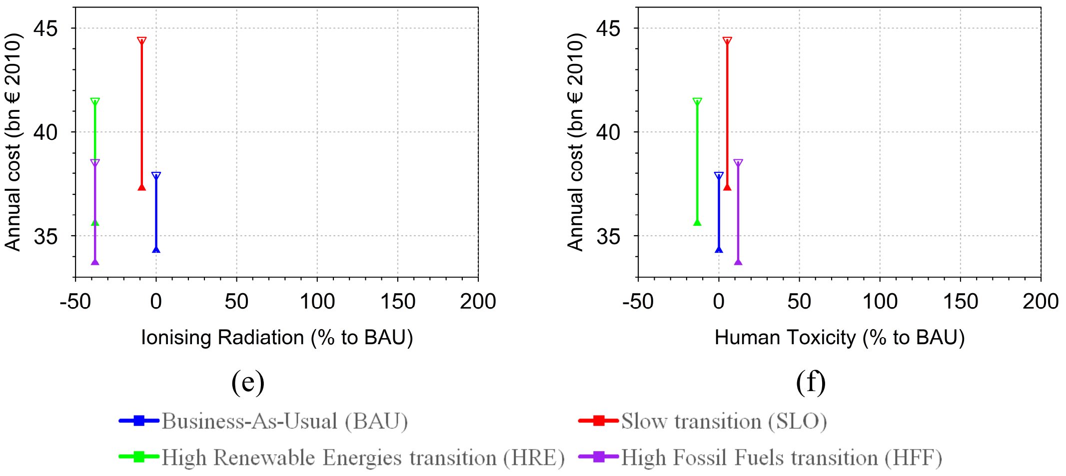
Figures 3.7 and 3.8 presents the trade-off graphs between costs and human health impacts. Transition scenarios' impacts according to most human health indicators are often higher than BAU scenario's along with their costs. As their costs are higher as well, many lose-lose situation can be observed in all the trade-off graphs of figure 5 except the one involving ionizing radiations. where the HFF scenario is in a win-win situation for a discount rate of 5%. Among the transition scenarios, a trade-offs trends can be observed. Indeed, in the trade-offs graphs of costs against climate change, photochemical oxidant formation, ozone depletion, and particulate matter formation indicators, as costs of transition scenarios increase, the impact according to those indicators decrease. Consequently, according to trade-offs graphs of human health indicators against costs, transition scenarios are mostly in a lose-lose situation compared to BAU scenario. Also, a trend of trade-offs involving transition scenario's cost increase along with human health impacts increase has been observed.



(a) (b)

(c) (d)

Fig. 3.7: Trade-offs of costs against ecosystem quality impacts
(a) climate change, (b) photochemical oxident formation, (c) particulate matter formation, (d) ozone depletion



(e) (f)

Fig. 3.8: Trade-offs of costs against ecosystem quality impacts
(e) ionizing radiations, (f) human toxicity

3.3.4 Trade-offs against hazardous waste

Figure 3.9 introduces the trade-off graphs between costs and safety aspects impacts. As for transition scenarios situation, chemical wastes generated by the BAU scenario are the lowest among all scenarios but BAU scenario has the highest generation of nuclear wastes. Consequently, a win-win situation and no lose-lose situation compared to the reference scenario, BAU scenario, can be observed on the trade-off graphs of costs against radioactive wastes generation: HFF scenario with a 5% discount rate has less impact on radioactive wastes and is in a win-win situation. However, according to the trade-off graph of cost against chemical waste, transition scenarios are in a lose-lose situation as their impact are higher than BAU scenario along with their costs. On the two trade-off graphs of costs against hazardous waste indicators, no clear trade-offs trends can be observed among the transition scenarios. As a consequence, there are no lose-lose situation compared to BAU scenario in the trade-offs between costs and radioactive waste generation but transition scenarios are in a lose-lose situation when trading costs against chemical waste. Furthermore, no trade-off trends involving transition scenario could be observed.

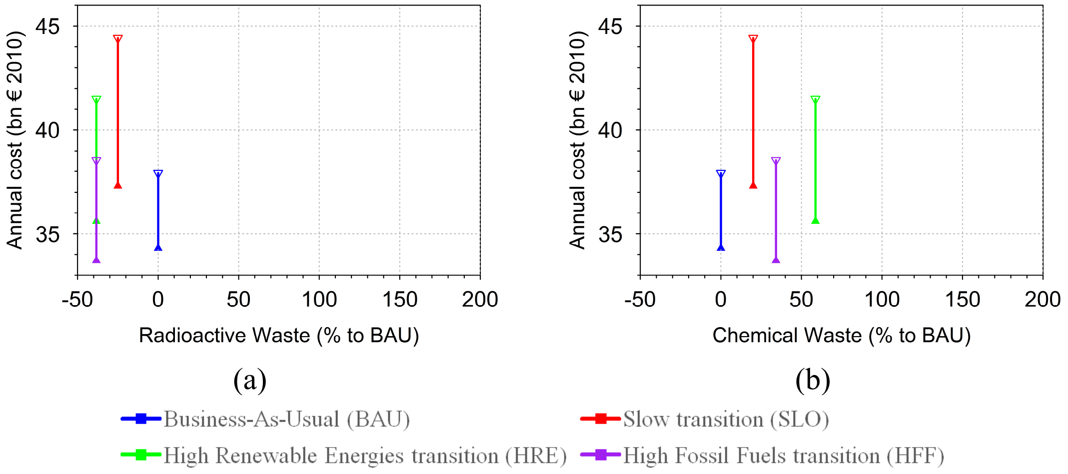


Fig. 3.9: Trade-offs of costs against resource availability impacts (a) radioactive waste, (b) chemical waste

3.3.5 *Trade-offs against safety*

Figure 3.10 introduces the trade-off graphs between costs and safety impacts. According to the severe accident indicator, the BAU scenario shows the lowest impact while being among the least expensive scenarios. As a result, no win-win situation compared to the reference scenario can be observed on this trade-off graphs but rather transition scenarios are in lose-lose situation. As for trade-off involving maximum accidental consequences, the HFF scenario is in a win-win situation for a discount rate of 5%. Indeed, HFF scenario with a 5% discount rate is less costly and has less impact on maximum accidental consequences. Among the transition scenarios, a positive trade-offs trends can be observed as severe accident decrease along with cost increase. As a consequence, a clear tendency of transition scenario being in a lose-lose situation has been observed with an exception of the HFF scenario being in a win-win situation for the cost and maximum accidental consequences trade-offs. Furthermore, trade-offs involving transition scenario’s cost increase along with an increase of severe accident risks impacts have been observed.

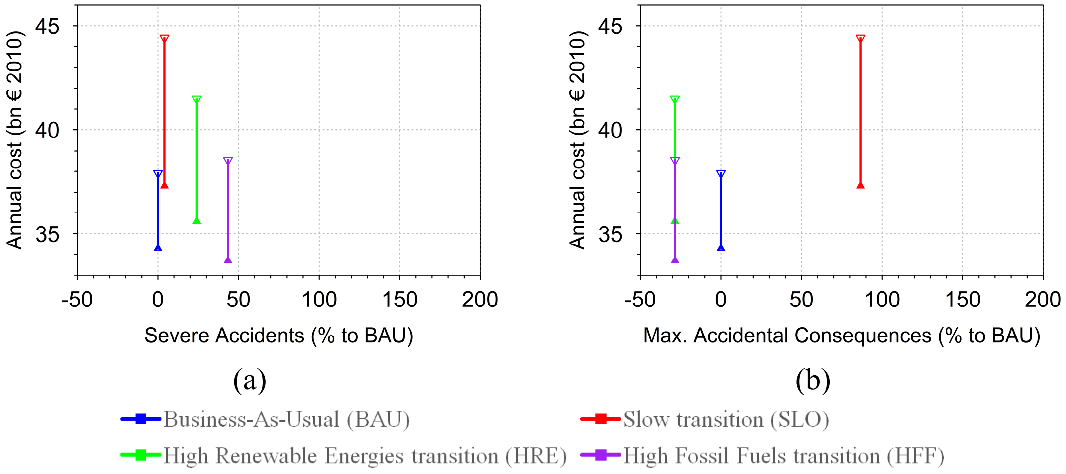


Fig. 3.10: Trade-offs of costs against resource availability impacts
(a) severe accident, (b) maximum accidental consequences

4

DISCUSSIONS

The discussion of the results will be organized in three parts. First, internal aspects of scenario are discussed through the interpretation of analytical results. Then, the external aspects of the current energy decision are discussed through the contextualisation of the results. The findings of this study are summarized by combining internal and external aspects in the form of a scenario by scenario SWOT analysis. Finally, recommendation to decision-makers concerning the integration of this energy decision support study in the decision-making process will be discussed.

4.1 Internal aspects: interpretation

The interpretation of the analytical results are organized according to the two following research question.

- Should we reduce nuclear share to 50% in France by 2025?
- How to reduce nuclear share to 50% in France by 2025?

Rather than providing answer to these questions, we will discuss how the analytical framework can contribute to supporting decision-makers in dealing with them. As for the first question, the strength and weaknesses of BAU scenario relatively to the other scenarios were studied based on trade-offs analysitical results. As for the second question, a comparisons of the three transition scenarios (SLO transition scenario (SLO), HRE transition scenario (HRE), and HFF transition scenario(HFF)) strength and weaknesses in term of performances and implied trade-offs were conducted.

4.1.1 Should we reduce nuclear share to 50% in France by 2025?

In order to understand what are the strengths and weaknesses of BAU scenario comparatively to transition scenarios, the analytical results are interpreted hereafter. Through the analysis of trade-off curves, we observed that the transition scenarios are never in a win-win situation according to trade-off curves of costs against 15 socio-environmental indicators (Fig. 3.4 to 3.10). The main reason is obviously because the BAU scenario is the least expensive scenario at 8% discount rate (34.3 bn €$_{2010}$) and the second least expensive at 5% discount rate (37.9 bn €$_{2010}$) and therefore cannot be dominated in most of the trade-off curves (Section 3.3). An exception to this pattern is HFF scenario that is less expensive than BAU scenario based on a discount rate assumption of 5%. At the same time, it performs better in terrestrial ecotoxicity, metal depletion, ionizing radiation, maximum accidental consequences and radioactive waste (Section 3.2). This being said, the HFF scenario suffers from significant impacts on climate change (+190% to BAU; Fig. 3.4 (a) and 3.7 (a)), freshwater eutrophication (+105% to BAU; Fig. 3.5 (h)), terrestrial acidification (+110% to BAU;Fig. 3.4 (e)), fossil depletion (+105% to BAU; Fig. 3.6 (b)) and photochemical oxidant formation (+130% to BAU; Fig. 3.7 (b)). However, BAU scenario is among the most impacting scenario when it comes to ionizing radiation, radioactive waste and maximum accidental consequences (Fig. 3.2 to 3.3). It has also average impact on terrestrial ecotoxicity, marine ecotoxicity, metal depletion, and human health (Fig. 3.2 and 3.3). As a result, the question would be whether the concerns of ionizing radiation, nuclear waste and accidental consequences have sufficient importance to balance the cost advantage and the numerous environmental aspects where BAU scenario performs well.

4.1.2 How to reduce nuclear share to 50% in France by 2025?

From the perspective of an energy transition, socio-environmental aspects traded off against costs are discussed for each transition scenario strategies analyzed in this study leading to an interpretation of their strengths and weaknesses. Leaving aside the BAU scenario, clear trade-offs trends of costs against socio-environmental impacts could be observed among transition scenarios in the 3rd level analysis (Section 3.3). It would be easier to grasp for decision-makers if the more we invest in scenario meant the less pressuring they will be on their socio-environment. Fortunately, this trend was often witnessed on trade-off curves of costs against climate change (Fig. 3.4 (a) and 3.7 (a)), terrestrial acidification (Fig. 3.4 (e)), fossil depletion (Fig. 3.6 (b)), ozone depletion (Fig. 3.7 (d)), severe accident or chemical waste (Fig. 3.10(a) and (b)). However, the opposite trend was also observed. According to trade-off curves of costs against terrestrial ecotoxicity (Fig. 3.4 (f)), metal depletion (Fig. 3.6 (a)), ionizing radiation(Fig. 3.8 (e)), maximum accidental consequences and radioactive waste (Fig. 3.10 (b) and Fig. 3.9 (a)), an increase of costs would go along with an increase of those impacts. This paradox indicates that strong trade-off among conflicting socio-environmental impact exists. Indeed, it reveals, that according to those three strategies, it is impossible to minimize all socio-environmental impacts as they evolve in opposite way with scenarios.

The SLO scenario is characterized by a very high annual generation cost (5% discount rate: 37.3 bn €$_{2010}$, + 8.75% to BAU; 8% discount rate: 44.4 bn €$_{2010}$, +17.2 % to BAU) and very similar impact pattern compared to BAU scenario (Section 3.3). Indeed, according to most ecosystem quality, resource availability and human health impact indicators, SLO is within 30% impact range compared to BAU scenario (Fig. 3.4 to 3.8). In terms of climate change, SLO scenario would be responsible for a 45% increase of greenhouse gases emissions (Fig. 3.4 (a) and 3.7 (a)) as its FF share is higher than in BAU scenario (Fig. 2.8). But, as it is a slow transition scenario, its nuclear share stands lower than in BAU scenario and as such its ionizing radiation impact and nuclear waste impacts are lower (respectively -10% and -25% to BAU; Fig. 3.8 (e) and 3.9 (a)). However, the European Presssurized Reactor (EPR) is considered as potentially more dangerous in case of accident and as a result the maximum accidental consequences indicators show a +85% compared to BAU scenario (Fig. 3.10 (b)). Consequently, SLO has, generally speaking, decent socio-environmental impacts compared to other transition scenarios but for a much higher cost. Compared to BAU scenario, it generates less radioactive waste against a much higher maximum accidental consequences.

The HRE scenario is less costly (5% discount rate: 35.6 bn €$_{2010}$, +3.79 % to BAU; 8% discount rate: 41.5 bn €$_{2010}$, + 9.4% to BAU) but has higher overall socio-environmental impacts (Section 3.3). As SLO, HRE has relatively low impact relatively to BAU scenario according to many socio-environmental indicators (within 40% of BAU; Fig. 3.4 to 3.8). However, its FF share being much higher than BAU scenario's (Fig. 2.8), greenhouse gases emission are also higher and climate change impacts are accordingly significant (+135% to BAU; Fig. 3.4 (a) and 3.7 (a)). Moreover, HRE scenario has, according to ozone depletion and chemical waste indicators, a higher impact (+60%; Fig. 3.7 (d) and 3.6 (b)). Nevertheless, as a 50% nuclear scenario, it produces less nuclear waste and ionizing radiations than BAU or SLO scenario (-50% to BAU; Fig. 3.6 (a) and 3.8 (e)). Furthermore, maximal accidental consequences are also lower (-30% to BAU; Fig. 3.10 (b)) even though severe accidents risk increased (+20%; Fig. 3.10 (a)) as accident happens more often in FFs plant life cycle than in other type of plants. As a result, HRE has show moderated socio-environmental impacts except for climate change and ozone depletion. The nuclear-related impacts such as nuclear wastes, maximum accidental consequences and ionizing radiations are logically decreasing along with nuclear energy share in the mix.

The HFF scenario has very high impact according to almost every socio-environmental scenario but is also the least expensive transition scenario (5% discount rate: 33.7 bn €$_{2010}$, -1.8 % to BAU; 8% discount rate: 38.5 bn €$_{2010}$, + 1.7% to BAU; Section 3.3). Indeed, its socio-environmental impacts often ranges from +70% to +130% compared to BAU scenario. Impact according to marine ecotoxicity (Fig. 3.4 (b)), terrestrial ecotoxicty (Fig. 3.4 (f)) and metal depletion (Fig. 3.6 (b)) are about the same than other transition scenarios. Key points for decision lies in the climate change and fossil depletion performances respectively +190% (Fig. 3.4 (a) and 3.7 (a)) and +105% (Fig. 3.6 (b)) to BAU scenario. On the other hand, the HFF having the same share of nuclear energy than HRE, it also has the same performances according to nuclear-related indicators (nuclear wastes, maximum accidental consequences and ionizing radiations; Fig. 3.9 (a), 3.10 (b), 3.8 (e)). Therefore, the trade-off in this scenario is whether we should sacrifice most socio-environmental concerns, especially climate change impacts, in the benefit of less generation cost and a reduction of nuclear-related issues. In addition of general trade-offs trends between transition scenario, the analysis revealed trade-offs implied in each of the scenario, emphasizing factors that would be key to the choice of a electricity generation scenario.

4.2 External aspects: contextualization

The decision to implement an electricity mix scenario is not only subjected to its performances. Indeed, the threat and opportunities induced by the context in which the decision is to be taken is of equal importance. Therefore, a contextualization from the perspective of economic, environmental and socio-political external factors was conducted.

4.2.1 Economic factors

Economic factors are very controversial in energy decision-making in France. Ever since the 2008 crisis, French GDP growth has been stagnating (Thomas and Lawson, 2013).

Unemployment has also been on a rise and inflation has gone beyond wages increase rate causing a decrease in people's purchase power (INSEE, 2013). In this precarious economic context, taxpayer money expenditures are watched by observers and austerity measures are implemented (AFP, 2013). Therefore, it seems hardly possible to envisage an investment to reform the electric generation fleet. However, a transition of the electricity generation system is also seen as a possibility to grow "green", leading to interesting rebound effect benefits. But, green growth has different meaning. The meaning of a development free of nuclear energy and fossil fuels giving a very high importance to renewable energy technologies or the meaning of a development free of greenhouse gases emission and harmful air emission by focusing on the development of nuclear energy technologies (Percebois, 2012). Each supporter of those two different green growth sees benefit in investing in it. On one hand, energy expert associations such as Global chance or Négawatt see RE as the future French industries should definitely involve and innovate in (Dessus and Laponche (2011) and Salomon et al. (2012)). On the other hand, the OPECST (Birraux et al., 2011) and Energies 2050 commission (Percebois, 2012) sees in the nuclear green growth an opportunity to maintain French mastery in nuclear activity well reducing the unit cost of G3 reactors through mass production. This opposition is directly connected to the employment issue. Whether jobs created by a newly established RE industry would be able to counter balance the one lost in the declining nuclear industry is highly uncertain and previous estimation were very different depending on which stakeholder is conducting it(Percebois, 2012). The issues of energy dependency and energy security are also significant when deciding the energy policy at the national level. In France, for political reasons, nuclear energy has always been presented as a primary energy in France, that is to say, an energy form available in nature without any transformation (Dessus and Laponche, 2011). However, France has no uranium resources, meaning the country is entirely dependent on foreign countries mainly Canada, Nigeria and Mali.

The two last countries are highly likely to be unstable (Stamford and Azapagic, 2011) and, in 2013 France sent troops against terrorist threats in Mali to protect it uranium mining assets. Consequently, it seems that nuclear energy cannot be considered as a primary energy ensuring energy security and independence. As other fossil fuels, oil and gas are posing the same problem as uranium. It is highly uncertain, that we can increase our consumption indefinitely and, moreover, the price of fuels are very volatile and therefore the more scenario are based on fossil fuels the more their costs become uncertain (OECD, 2011).

4.2.2 Environmental factors

From an environmental perspective, there is a very pressuring external forces to mitigate some environmental impact such as climate change. Indeed, France committed itself to reduce its nation-wide greenhouse gases emission at several levels (Ministère du Développement durable, 2013). With the POPE law, France is to divide by 4, compared to the level of 2000 ,its emission of per capita greenhouse gas emissions by 2050. Meanwhile, France also adopted the European Union climate and energy package, thus engaging itself to cut greenhouse gases emission by 14% between 2005 and 2020. Furthermore, France was a signatory of the Kyoto Protocol until 2012 and as such stabilized its greenhouse gases emission over 2008-2012 based on 1990 levels. Besides climate change, there is another significant environmental question which remains unanswered in France: the nuclear waste final disposition. This question is carefully being avoided in government reports that deal with the future of nuclear power (Dessus and Laponche, 2011).However, in France, nuclear wastes are using the waste reprocessing techniques. Theoretically, the components of spent fuel are chemically separated to be reused. Yet, Global Chance nuanced this statement:

> *The efficiency of the strategy of reprocessing is usually summarized by a lapidary figure declined in any official communication on the topic: "through reprocessing, 96% of spent fuel materials are recycled". However, this figure does*

> *not reflect reality at all because 97% of these reusable materials are not actually recycled in the current industrial conditions. (Dessus and Laponche, 2011)*

Even for the 3% spent fuel which are recognized as waste, there is no solution. In most nuclear-powered countries nuclear waste are temporary cooled down in pool and then buried deeply in the grounds for thousands of years. A recent example of this repository system can be found in Finland where nuclear waste will be sealed for 100 000 years 500 m deep in the ground. Observers denounce the extreme risk involved in this depository system and some already imagines that in a few thousand years, explorers would dig down there in search of a treasure(Duncan, 2013). As a result, there are no concrete nuclear waste final depository solution implemented in France.

4.2.3 Socio-political factors

In a more social perspective, in the wake of Fukushima's nuclear accident, people's awareness of nuclear accident risk and potential damages increased (IFOP, 2011). This aspect of risk management is also left aside in government-ordered documents and therefore Fukushima's accident was a turn for people to realize the potential danger of nuclear power plant. A rise in renewable energy public support (Ipsos Public Affairs, 2013) and a decrease in nuclear energy's makes energy transition a suitable political choice. Also, ever since Fukushima nuclear disaster and Germany's moratorium to close Fessenheim nuclear power plant, France is pushed by its phasing out neighboring countries to engage in a transition. At the same time, electricity exports to those same neighbors has increased enabling them to carry on their plan to switch to more suitable electricity generation system (RTE, 2012).

Consequently, it seems that external forces are coercing energy decisions. The context in France and the numerous global energy issues are adding up uncertainty and complexity to the energy transition decision.

4.3 Combination of internal and external aspects: SWOT analysis

In order to provide a basis for the coming negotiation among decision-makers, the findings of this study were summarized, combining both interpreted results from the assessment and the trade-off analysis, and external forces through contextualization, SWOT analysis were carried out.

4.3.1 Business-As-Usual scenario

As a summary of the findings of this research towards the energy transition decision support, table 4.1 shows the SWOT analysis of the BAU scenario. The BAU scenario representing the current strategy, the SWOT analysis presents all the findings of the present study related to the decision of transition itself. BAU scenario's competitive annual generation is certain advantage in a country where financial crisis have been long installed. Furthermore, as it is a nuclear-powered scenario (76%; Fig. 2.8), we think that BAU scenario's implementation would be a positive sign of trust from the French government to its nuclear industry which would potentially benefit the nuclear industries international situation. But, even though it would contribute to the survival of the nuclear industry, France would miss the chance to develop a world's top renewable energy industry by denying the opportunity of expanding it renewable energy domestic market. From the perspective of employment, it means that employments in nuclear industry would be preserved, but there would be few job created in the renewable energy industry. Besides, the low greenhouse gases emission is definitely an advantage as France committed itself to reduce its emission at the European level. The low fossil depletion impact is also an useful strength in a world threaten with rapid and high variation of fossil fuels prices. The low impact on ecosystem quality and health is very important, but still we can doubt the fact that it would counterbalance public acceptance of nuclear-powered scenario as nuclear-acceptance decreased in the wake of Fukushima's nuclear accident. Furthermore, the very high nuclear waste generation of this scenario is a very risky bet taking account that nuclear-powered country have no concrete plan to dispose of radioactive waste. Lastly, BAU scenario capacity production would enable France to maintain its export capacity to countries that will increasingly need it as they phase out nuclear energy. At the same time, those same countries sees nuclear energy accident risk too high and pressure France to follow their example and engage itself in an energy transition.

Tab. 4.1: SWOT analysis of the BAU scenario

Internal factors	
Strengths	**Weaknesses**
Competitive annual generation cost (Section 3.3) Low greenhouse gases emission and fossil depletion impact (Fig. 3.4 (a) and 3.6 (b)) Low impact on ecosystem quality and health (Sect. 3.3.1 and 3.3.2)	Very high radioactive waste generation (Fig. 3.9 (a)) High accidental consequences (Fig. 3.10 (b))
External factors	
Opportunities	**Threats**
Financial crisis (Sec. 4.2.1) Declining French nuclear industry (Sec. 4.2.1) High demand for electricity exports (Sec. 4.2.1) Greenhouse gases emissions reduction objectives (Sec. 4.2.2)	Possibility of creation of a French renewable energy technology industry (Sec. 4.2.1) Still no radioactive waste final disposal solution (Sec. 4.2.2) Nuclear acceptance has decreased (Sec. 4.2.3) Phasing out European neighbours pressure (Sec. 4.2.3) Volatility of Fossil Fuels prices (Sec. 4.2.1)

As a summary of the findings of this research towards the differents scenario of energy transition, tables 4.2, 4.3, and 4.4 presents the SWOT analysis of, respectively, the SLO transition scenario, the HRE transition scenario and the HFF transition scenario. They gathered combined discussions on internal and external factors on the decision of the strategy to adopt if a transition is decided.

4.3.2 Slow transition scenario

As for SLO transition scenario (table 4.2), from an economic perspective we can infer that it will be difficult to implement such a costly scenario in a time of financial crisis. However, SLO scenario implementation could lead to a revival of the declining French nuclear industry as mass production of generation 3's EPR would decrease its unit cost and make it more competitive on the international civil nuclear market. That would lead nuclear industry to secure employment in its field while slowly creating job in the field of renewable energy technology. The transition to more renewable energy being slow, France might lose the chance to develop a world's top renewable energy industry. At the same time, the impact on ecosystem quality and human health are relatively low compared to other transition scenario. This being said, it may not be enough to get public support on this scenario's implementation as this scenario includes the construction of several new nuclear power plants and very high maximum accidental consequences. However, this transition being slow, it also has a low fossil fuels share and therefore relatively low greenhouse gases emission and fossil depletion impact. This would then makes it easier for France to respect its engagement on the reduction of greenhouse gases emission and it would also make the country less vulnerable to the volatility of fossil fuels prices. The radioactive waste generation is relatively high compared to other transition scenario which is very controversial as there are still no final disposition system of nuclear waste. Besides, the slow transition makes it possible to maintain France's electricity export capacity to nuclear phasing out neighbours. However those countries wouldn't support the implementation of a such a scenario as accidental consequences has no borders.

Tab. 4.2: SWOT analysis of the SLO transition scenario, DR stands for discount rate

Internal factors

Strengths	**% to BAU**	**Weaknesses**	**% to BAU**
Relatively low greenhouse gases emission and fossil depletion impact (Fig. 3.4 (a) and 3.6 (b))	+40%	Very high annual generation cost	5% DR: +8.8% 8% DR: +17.2%
Relatively low impact on ecosystem quality and health (Sect. 3.3.1 and 3.3.2)	+20% ∼ +40%	Very high maximum accidental consequences (Fig. 3.10 (b))	+90%
		Relatively high radioactive waste generation (Fig. 3.9 (a))	−20%

External factors

Opportunities	**Threats**
Declining French nuclear industry (Sec. 4.2.1)	Financial crisis (Sec. 4.2.1)
High demand for electricity exports (Sec. 4.2.1)	Possibility of creation of a French renewable energy technology industry (Sec. 4.2.1)
Greenhouse gases emissions reduction objectives (Sec. 4.2.2)	Still no radioactive waste final disposal solution (Sec. 4.2.2)
	Nuclear acceptance has decreased (Sec. 4.2.3)
	Phasing out European neighbours pressure (Sec. 4.2.3)
	Volatility of Fossil Fuels prices (Sec. 4.2.1)

4.3.3 50% Nuclear with High Renewable Energies transition scenario

As for the HRE transition scenario (table 4.3), it has a relatively high generation cost compared to other transition scenario and as such can be difficult to implement during a financial crisis. However, it would be an opportunity to develop a world's class renewable energy industry and create jobs in this field. This would, however, happens at the expense of the decline of the country's nuclear industry and the jobs it sustains. But, this would come along with nuclear-related issues mitigation, such as the generation of radioactive waste, ionizing radiation emissions and maximum accidental consequences. It would be well perceived from the public as nuclear acceptance has decreased and from the perspective of phasing out neighbours countries that pressured France to follow their strategy even if they wouldn't be able to import electricity anymore. Besides, as there are still no final waste disposal concrete plan existing, the reduction of its generation rate seems to be a necessity. Nevertheless, HRE also involves mid-range impacts on ecosystem quality as well as human health. Its greenhouse gas emissions are very high and are in clear opposition to France's commitment to reduce its climate change impacts. Lastly, its relatively high dependence on fossil fuel, makes it more vulnerable to the volatility of fossil fuels prices.

Tab. 4.3: SWOT analysis of the HRE transition scenario, DR stands for discount rate

Internal factors			
Strengths	**% to BAU**	**Weaknesses**	**% to BAU**
Lower ionizing radiation emissions and nuclear waste generation (Fig. 3.8 (e) and 3.9 (a))	−40%	High annual generation cost (Section 3.3)	5% DR: +3.8% 8% DR: +9.4%
Lower maximum accidental consequences (Fig. 3.10 (b))	−30%	Mid-range impacts on ecosystem quality and health (Sect. 3.3.1 and 3.3.2)	+30% ∼ +60%
		Very high greenhouse gases emissions and fossil depletion impact (Fig. 3.4 (a) and 3.6 (b))	+130% +30%
External factors			
Opportunities		**Threats**	
Well accepted political choice as nuclear acceptance decrease (Sec. 4.2.3) Development of the French renewable energy technologies industry (Sec. 4.2.1) Job creation in the renewable energy industry (Sec. 4.2.1) Still no radioactive waste final disposal solution (Sec. 4.2.2) Phasing out European neighbours satisfaction (Sec. 4.2.3)		Financial crisis (Sec. 4.2.1) Decline of the nuclear industry (Sec. 4.2.1) Reduction of electricity export capacity (Sec. 4.2.1) Job losses in the nuclear industry (Sec. 4.2.1) Decrease of energy independency and consequent volatility of energy price (Sec. 4.2.1) Commitment on greenhouse gases emissions reduction (Sec. 4.2.2)	

4.3.4 50% Nuclear with High Fossil Fuels transition scenario

For HFF (table 4.4), it is very cost competitive relatively to transition scenario and even compared to BAU, which is sure advantage as the financial crisis persist. Furthermore, as this scenario focussed on fossil fuels power plant's expansion rather than renewable energies, the creation of job in the field of renewable energy technology compared to HRE would be relatively lower. The transition to more renewable energy being rather slow, France might lose the chance to develop a world's top renewable energy industry. As this scenario is a transition to 50% nuclear, it would also mean a decline of the nuclear industry and the reduction of employment it generates. On the other hand, it would also mean that the maximum accidental consequences, as well as the ionizing radiation emissions and nuclear waste generation would be lower compared to nuclear-based scenarios. This would increase the acceptance of such a transition scenario as nuclear acceptance decreased. Besides, phasing out neighbours countries would be satisfied as they are pressuring France to follow their lead. However, HFF scenario has high impact on ecosystem and health and very high greenhouse gases emissions. This is could definitely prevent France from achieving its emission reduction objectives. The fossil fuel depeletion impact indicate that France will be very much dependant on foreign fossil fuels and therefore very much vulnerable to every change in its price.

Tab. 4.4: SWOT analysis of the HFF transition scenario, DR stands for discount rate

Internal factors

Strengths	**% to BAU**	**Weaknesses**	**% to BAU**
Competitive generation cost (Section 3.3)	5% DR: −1.8% 8% DR: +1.7%	Highest greenhouse gases emissions and fossil depletion impact (Fig. 3.4 (a) and 3.6 (b))	+190% +105%
Lower maximum accidental consequences (Fig. 3.10 (b))	−30%	Highest impact on ecosystem quality and health (Sect. 3.3.1 and 3.3.2)	+70% ∼ +100%
Lower ionizing radiation emissions and nuclear waste generation (Fig. 3.8 (e) and 3.9 (a))	−40%		

External factors

Opportunities	**Threats**
Financial crisis (Sec. 4.2.1) Well accepted political choice as nuclear acceptance decrease (Sec. 4.2.3) Satisfaction of European neighbors (Sec. 4.2.3)	Decline of the nuclear industry (Sec. 4.2.1) Reduction of electricity export capacity (Sec. 4.2.1) Job losses in the nuclear industry (Sec. 4.2.1) Slow development of the French renewable energy technologies industry (Sec. 4.2.1) Job creation in the renewable energy industry (Sec. 4.2.1) High decrease of energy independency and consequent volatility of energy price (Sec. 4.2.1) Engagement regarding greenhouse gases emissions reduction (Sec. 4.2.2)

4.4 *Recommendations to decision-makers*

The analytical framework of the present study provided an interesting perspective on the trade-offs between costs and socio-environmental concerns implied in energy decision. In previous French energy decision support studies (Percebois, 2012), the analysis was rather informal, subjective and lacked structure. Anakyzed scenario were provided by industries in the energy field, leading independant energy experts to accuse the commission of producing biased reports. The socio-environmental impact were superficially and informally considered and the scenario evaluation processes were non transparent. As a conclusion, Percebois (2012) recommends the pursue of the full nuclear strategy (coresponding to the BAU scenario in the present study). However, this study has shown that this practices are not necessary and not acceptable. The present study is abased on a Multi-Criteria Analysis framework and therefore formally structured. Scenario were self made based on the potential alternatives pointed out in previous literature. Evaluation process, are replicable and therefore transparents and the studies integrates 21 socio-environmental indicators. The analysis carried out involves complex trade-offs among conflicting aspects and, therefore, no hasty conclusions and generalizations should be drawn directly from the scenarios or their overall performances. Moreover, external factors are putting energy decisions under a significant constraint and should be assessed along with the scenarios. The combination between external aspects from contextualization and internal aspects from analytical results interpretation provided a valuable and necessary input to this decision support study. However, this study directly question the necessity to promote a scenario as an outcome. Indeed, we have shown that each energy decision implies trade-offs that are controversial. As a result, the decision to privilege economic concerns or the mitigation of any socio-environmental impacts over safety includes value judgments that analysts have no legitimacy to make.

We would like to propose two main recommendations based on this study findings and our observations. Firstly, we believe that decision-making support study should be used not only as a way to provide technical information to decision-makers but also should also be fully integrated into the decision-making process to structure it. We think that, too often in France, the debate as well as the decision support studies that are focused on which option to support among nuclear, fossil fuels or renewable rather than on which objectives should be priorities and what are the trade-offs among those objectives that are acceptable. We believe that this is an obvious example of the total separation between decision support and decision making process as well as a certain lack of objectivity. As promoted by Andrews (1992), decision making support should aim at "handling technical complexity by providing an expert analysis team to ensure adequate technical detail, while minimizing its "black box" nature" with "assisted negotiation to (...) resolve contentious planning debate". As shown in the method part of this thesis, this were Multi-Criteria Decision Analysis (MCDA) is meant to do. Figure 4.1 and table 4.5 provides a simple working example of MCDA. From the weigth repartition set among the different criteria representing three decision-makers preferences, a simple MCDA model, the Weighted Sum is applied to get the most optimal scenario for each decision-makers. Based on those results, the decision-makers can resolve the differences and negotiate from information provided by the trade-offs analysis. On the other hand, conducting MCDA-based decision-support studies is not possible to apply in the current non-transparent decision-making process. This requires being able to list up decision-makers and to get their interest and preferences, which seems impossible to achieve (Hymans, 2012). Therefore, in order to make an integration of decision-support possible, the transparency of data, decision-making process and its stakeholders is required.

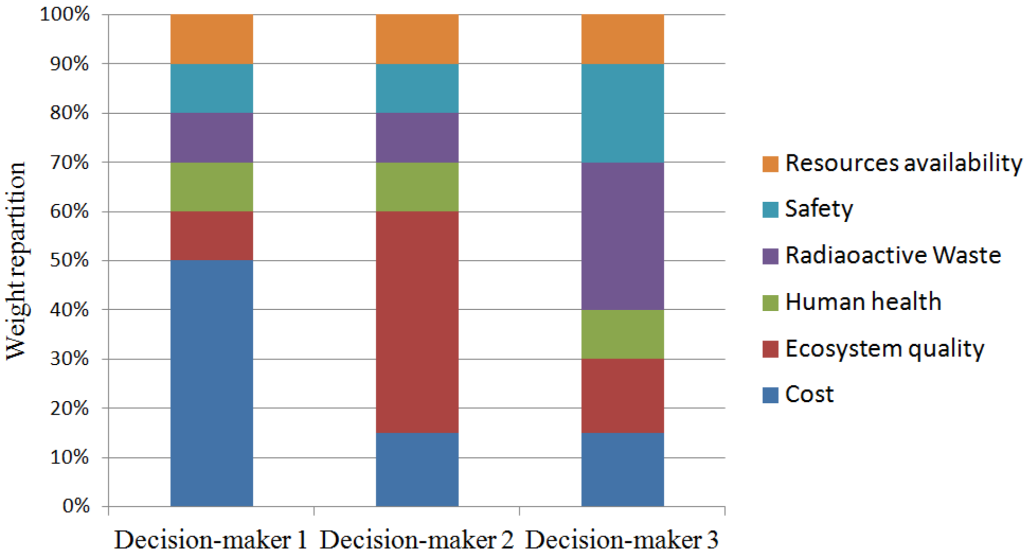


Fig. 4.1: Example of weight set from the perspective of three decision-makers

Tab. 4.5: Scenario ranking for each decision-maker

Rank	**Decision-maker 1**	**Decision-maker 2**	**Decision-maker 3**
1	BAU scenario	BAU scenario	HRE scenario
2	HFF scenario	SLO scenario	BAU scenario
3	HRE scenario	HRE scenario	SLO scenario
4	SLO scenario	HFF scenario	HFF scenario

Secondly, as stated by the French accountancy court, the *Cours des Comptes*, we believe that it is essential to systematically analyze the socio-environmental aspects of each energy options (CdC, 2012). We have observed that the informal integration of socio-environmental aspects has lead to factual mistakes and hasty generalization. For instance, in the energy debate and in the energy decision support commission's report, a strong will to put an environmental-friendly label on scenarios can be observed (Percebois, 2012). But, according to the present study results, an environmental-friendly scenario does not exist. There are scenarios that perform better according to some of the socio-environmental indicators but are the worst performers in others. The Business-As-Usual scenario is the perfect example of this situation. It is the best performers on many indicators in ecosystem quality, resource availability and human health, but it has among the worst impact in term of hazardous waste and safety.

5

CONCLUSION

5.1 Summary

In this study, the 4 main potential strategies for a transition of the French electricity generation fleet towards a reduction of the share of nuclear energy by 2025 were analyzed within the energy transition debate initiated by François Hollande. In order to provide decision-makers with necessary information to engage in negotiations based on objectives and trade-offs among those objectives, multi-criteria analysis was conducted from the perspective of both economic and socio-environmental aspects. It resulted in the exposure of trade-offs among costs against indicators representing 5 socio-environmental concerns: impact on ecosystems, resources availability, human health, hazardous waste, and safety. Results have shown that energy decision involves complex trade-offs among numerous conflicting objectives that makes impossible hasty conclusion on the existence of an environmental-friendly transition. In addition of general trade-offs trends between transition scenarios, the analysis revealed trade-offs implied in each of the scenario, emphasizing factors that would be key to the choice of a electricity generation scenario.

The decision of whether to implement the transition itself is subjected to significant compromise. Indeed, the Business-As-Usual scenario represent a very cost competitive option and has the lowest impacts on ecosystems and health as well as climate change. Nevertheless, the issues of radioactive waste, ionizing radiations and accidental consequences are particularly significant with this scenario.

If a transition is decided, which transition strategy to adopt among a slow transition combined with an acceleration of G3 reactor commissioning (SLO scneario), a reduction of the nuclear energy share to 50% combined with high renewable energies expansion (HRE scenario) and a reduction of the nuclear energy share to 50% combined with high fossil fuels use (HFF scenario) is also very controversial. SLO transition option is at the core of a trade-offs between very high cost and maximum accidental consequences, still high radioactive waste generation and relatively low greenhouse gases emissions compared to other transition scenario. As for, HRE transition scenario, it involves moderated cost socio-environmental impacts except for climate change and ozone depletion, which are very high. HFF transition scenario has very high impact according to almost every socio-environmental scenario but is also the least expensive transition scenario. On the other hand, for the two 50% nuclear transition scenarios, the nuclear-related impacts such as nuclear wastes, maximum accidental consequences and ionizing radiations are logically decreasing along with nuclear energy share in the mix.

In order to provide all the necessary information to find the optimal solution to France's energy transition, the trade-offs analytical results were confronted to a contextualization conducted according to the three pillars of sustainability: economic, environmental an social contextualizations.Therefore, the outcome of this support study lies in the combination on both the interpretation of the results of the trade-off analysis and their contextualization in the form of a SWOT analysis. Therefore, this study study provides guidelines for further negotiations and debate on energy planning.

Trade-off analysis is an essential component of decision support. Decision-makers need to consider which trade-offs are implied by each decision as well as how much of an objective they are ready to give up for another in order to make consistents decisions. To make it possible, decision support should be provided during the whole decision-making process, including technical evaluation and formal structure. Therefore, recommendations to decision-makers include the improvement of decision-making process' transparency to enable a concrete integration of decision support studies and the formal systematic inclusion of socio-environmental concerns in the decision-making process.

5.2 Study Limitation

This study is a prospective analysis and as such has necessarily to tackle the issues of uncertainty and data availability. Costs are hardly available for every technology and especially for nuclear power plant technologies as their dissemination are up to industries and sometimes considered as industrial secrets. Furthermore, even though the dispersion of emerging technologies such as tidal power or pumped storage hydropower plants will be limited in 2025, they should be included in such a prospective study as they have a role to play later on in the future. However, it was not possible to get data cost and life cycle analysis data on their early days of development. Besides, as observed in this study, when available cost data are highly uncertain as they depend on a very sensitive discount rate. As for life cycle analysis data, they are often averaged data for a specific location and involve uncertainties that were hard to take into account. Furthermore, factors such as employment or the volatility of fossil are very significant to the choice of an energy option but highly uncertain and therefore considered as external in the present study.

5.3 Further research

Further research on France energy planning support will involve three different research fields. The first one goes along with the recommendations to decision-makers discussed in section 4.4 and include the development of a MCDA-based framework for a further integration of decision support in the French energy decision-making process is to be developed. Working hands in hands with decision-makers, researchers should work on developping a Multi-Criteria Decision Analysis framework capable of integrating French decision-makers preferences and objectives. Secondly, further decision support study could also aim at including broader range of economic, environmental and social criteria by conducting deeper research on sustainability assessment of energy technologies in order to take into account more aspects. Efforts could also be put towards the internalization of external forces as criteria of decision. Issues like employment, impact on overall economy or on utility companies, and social acceptance are also key to shaping an optimal solution to energy planning. Thirdly, numerous scenarios development representing different strategies and based on more advanced supply side models but also demand side management options such as potential policies to implement energy efficiency and energy sobriety concepts are needed. For instance, it could focus on the development of a different renewable energy scenario. Indeed, comparatively to other scenarios and especially nuclear-powered one, BAU and SLO, the HRE scenario's socio-environmental impacts are often larger. This can be explained by the actual share of fossil fuels inside the HRE mix. Indeed as Renewable Energies are intermittent energies, that is to say, their actual electricity production depend on unpredictable event such as wind, sunlight or precipitations. As a consequence, the renewable energies technologies' output power cannot be increased to match daily peak demands and fossil fuel power plant have to back up renewable energy power plant to assume this function. Therefore, HRE scenario's fossil fuels share (16.7%) is much higher than BAU (6.7%) and SLO (9.7%). However, it would be interesting take into account the peak-electricity import potential as well as measures to reduce electricity consumption such as improving the efficiency of the grid and electric devices and decreasing the electricity needs through the sobriety concept as proposed by NégaWatt (Salomon et al., 2012).

Finally, we believe that the findings of this master's thesis could be applied to any of the numerous countries where an energy transition is discussed. Still, it is important to evaluate all the differences between France and the targeted countries in order to adapt the findings of this study.

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