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EVALUATIONS ON THE SUSTAINABILITY OF ENERGY SCENARIOS AND ROLE PLAYED BY NUCLEAR ENERGY

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ABSTRACT

The concept of sustainable development has been deeply influenced by the publication of the *Our Common Future* report in 1987. Since then the scientific community has continued its efforts to identify principles, indicators, and methodologies that could better fit the inherent multi-dimensional essence of this concept and its assessment.

Researchers have identified a series of principles considered fundamental for a proper assessment of sustainable development. The dynamic, normativity, equity, and integration principles should underpin any assessment of sustainability. This approach requires methodologies and tools suitable for a proper analysis of sustainability.

In this view, the assessment of nuclear energy sustainability is a challenging task where economic aspects, environmental objectives, and social tensions are pronounced. The International Atomic Energy Agency has developed a framework for the assessment of nuclear energy sustainability named INPRO methodology. The analysis undertaken on the literature, the IAEA's official documents, and the consideration of the basic principles contained in the INPRO methodology have confirmed that some elements fundamental for an assessment of sustainability are underrepresented in the IAEA's methodology.

This document presents a schema for the assessment of nuclear energy that pursues the objective to overcome some weak aspects noted in the course of review: consideration of stakeholders, democratic participation in decisions, analysis of subjective aspects, and consideration of alternative options for the development of the power sector. These elements have been coupled with a tool capable of catching the key requirements of the INPRO methodology.

Non-quantitative indicators and a multi-criteria decision-making approach are hosted in the layout to construct a framework more consistent with the indications given by the scientific community on the methodology for the assessment of sustainability.

The document presents an application where nuclear energy and most relevant competing technologies for electricity generation are considered in the assessment.

SOMMARIO

Il concetto di sviluppo sostenibile è stato profondamente influenzato dalla pubblicazione del rapporto *Our Common Future* nel 1987. Da allora la comunità scientifica ha continuato i propri sforzi per identificare principi, indicatori e metodologie che possano interpretare al meglio l'essenza multi-dimensionale di questo concetto e della sua valutazione.

I ricercatori hanno identificato una serie di principi considerati fondamentali per la valutazione di uno sviluppo sostenibile. Ogni valutazione di sostenibilità dovrebbe essere basata su elementi di dinamicità, normatività, equità e integrazione quali parti integranti dell'indagine. Questo approccio richiede metodologie e strumenti adatti per una adeguata analisi di sostenibilità.

In questa prospettiva, la valutazione della sostenibilità dell'energia nucleare è un compito complesso tenuto conto del fatto che aspetti economici, obiettivi ambientali e tensioni sociali sono pronunciati. L'Agenzia Internazionale per l'Energia Atomica ha sviluppato un metodo per la valutazione della sostenibilità dell'energia nucleare chiamato metodologia INPRO. L'indagine effettuata sulla letteratura, documenti ufficiali IAEA, principi base della metodologia INPRO hanno confermato che alcuni aspetti fondamentali nella valutazione della sostenibilità appaiono non sufficientemente considerati nella metodologia adottata dalla IAEA.

Questo documento propone un approccio alla valutazione della sostenibilità dell'energia nucleare che si pone l'obiettivo di superare alcuni aspetti deboli rilevati nell'analisi: considerazione degli stakeholders, partecipazione democratica alle decisioni, inclusione di aspetti soggettivi nella valutazione, considerazione adeguata di opzioni alternative per lo sviluppo del settore elettrico. Questi elementi sono stati accoppiati con uno strumento di analisi in grado di interpretare le richieste chiave della metodologia INPRO.

L'uso di indicatori non-quantitativi e l'utilizzo di un approccio multi-criteria decision-making sono stati inseriti nella struttura dell'analisi con l'obiettivo di ottenere una maggior consistenza con le indicazioni fornite dalla comunità scientifica riguardo alla metodologia per la valutazione della sostenibilità.

Il documento presenta un'applicazione nella quale l'energia nucleare e le tecnologie più rilevanti che competono per la generazione elettrica sono considerate nell'analisi di sostenibilità.

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1. INTRODUCTION

In 2010, total CO_2 emissions of the energy sector amounted to 30.5 Gt with an increase of about 5% if compared with the emissions recorded in 2009 (IEA, 2012). In 2008, emissions had diminished in coincidence of the peak of a global economic crisis. In 2010, the contribution of electricity generation to CO_2 emissions was 11.8 Gt. In 2012, total CO_2 emissions of the energy sector increased to 31.6 Gt with a contribution of the power sector of 13.2 Gt (IEA, 2014). More recent data confirms this trend with global emissions reaching in 2013 a level of 32.2 Gt (IEA, 2015).

Greenhouse gases (GHG) emissions are responsible for an increase in the global mean surface temperature that the scientific community judges leading to significant and irreversible climate changes. Projections indicate that the global mean surface temperature is currently headed for an increase higher than 4°C in comparison with pre-industrial conditions (IPCC, 2013). Reduction of emissions and decarbonization of the power sector are therefore mandatory to avoid dramatic effects on climate. This objective is even more urgent as projections agree on the fact that electricity demand will increase higher than primary energy needs. By 2040, electricity generation will move from 22721 TWh (2012) to values in the interval 35043-44003 TWh (IEA, 2014). Recent data confirms these indications (BP, 2016; EXXONMobil, 2016).

The decarbonization of the power sector is certainly an ambitious objective (IEA, 2012; IEA, 2013a; IRENA, 2015). This objective could be pursued through different strategies: deployment of more efficient technologies; switch to lower carbon fossil fuels; increase the contribution of renewables and nuclear; develop plants for carbon capture and storage (CCS) (IEA, 2012). Estimations on the contribution of nuclear energy to electricity demand accounts for values lying in the interval 10-18% (IEA, 2013a). In recent projections the growth of nuclear energy in terms of primary energy lies in the interval 1.6-1.9% per year (BP, 2016; EXXONMobil, 2016; IEA, 2014). Despite these indications and after a decade of so-called “nuclear renaissance” the accident occurred at the Fukushima-Daiichi nuclear power plants has re-opened the debate over the future of nuclear energy.

Some countries have chosen to phase out nuclear (e.g., Germany, Switzerland, and Belgium) or to cancel their plans to re-start nuclear energy (e.g., Italy). However, most countries confirmed that they will keep nuclear in their power mix or will develop it further, albeit at a less ambitious rate than previously announced. Some countries that have been considering the introduction of nuclear energy for the first time (e.g., Indonesia, Thailand, Malaysia, and the Philippines) are delaying and, in some cases, revising their plans. In 2016, 450 nuclear power plants have been in operation and 60 under construction. Overall, 30 countries deploy nuclear energy for a production that in 2015 was 2441 TWh (PRIS, 2016).

In the aftermath of the accident occurred in Japan, countries operating nuclear reactors carried out stress tests to assess the safety of their nuclear plants under extreme natural events (earthquakes and flooding). Lessons learned from this accident are expected to increase the stringency of safety standards. More investments in safety upgrades and retrofit are foreseen. In addition, the outcomes of stress tests could make more difficult the extension of plant lifetime leading to an acceleration in closures. Similarly, more complex procedures for siting and licensing could create additional difficulties to the start of new projects. All these factors could further turn to skeptical the attitude of the public opinion towards nuclear energy (IEA, 2013b). Severe accidents have usually a strong impact on the acceptance of nuclear energy.

Therefore, if on the one hand nuclear technology is acknowledged to have high capabilities to tackle human-induced climate changes and for that reason included in strategies to limit GHG emissions, on the other hand issues such as safety and radioactive waste may cause an opposition of the public opinion that could seriously limit its development.

The debate over the use of nuclear energy is ample and addressing several aspects such as cost, availability of natural uranium, proliferation risks, safety, and radioactive waste. The discussion requires to consider economic, environmental, social, and institutional factors. . Therefore, it can be recognized as a sustainability assessment.

Despite the fact that sustainability or sustainable development is commonly used in the everyday language, this concept is widely studied by the scientific community. Nuclear energy is a typical example that points out how difficult and complex is the definition of sustainability and its assessment.

The concept of sustainable development and sustainability assessment (SA) has evolved mainly after the publication of the *Our Common Future* report (1987) and the Conference on Climate Change held in Rio de Janeiro (1992). Since then these concepts have been studied leading to the definition of a series of principles that should form the basis of a sustainable development and properly acknowledged in its assessment (Waas et al., 2011).

Authors list following principles:

- normativity principle;
- equity principle;
- integration principle;
- dynamic principle (Waas et al., 2011).

The first principle states that the concept of sustainability depends entirely on the views and values on which the interpretation of development and the evaluation of legacies to future generations are formed. By consequence, subjective and normative aspects should play a proper role besides scientific and rational ones in the assessment. The second principle affirms that a sustainable development should be strictly linked to equity. This principle has many facets: intergenerational equity (legacy to future generations), intra-generational equity (fair distribution of burdens and benefits), geographical (local vs. global). According to this principle decision-making procedures should involve the democratic participation and consideration of all stakeholders. The integration principle requires to harmonize traditional development objectives with more recent and well-recognized environmental and social issues (Waas et al., 2011). The fourth principle points out that sustainable development is a process of change, a movement towards sustainable objectives that could be even changed in itinere.

The study of Huge´ et al. (2011) affirms that sustainability assessments should comply with all aforementioned principles and structure the complexity of the matter under consideration through the use of multi-criteria decision-making (MCDM) methodologies and tools. Waas et al. (2011) remind the need to include uncertainties in the assessment by applying a precaution approach that avoids even poorly understood risks of serious or irreversible damages to the environment or society. Authors suggest to design for surprise, and to manage for adaptation.

The application of sustainable development principles brings the need that stakeholders play a role in the assessment and decision-making through different manners of democratic participation and share of responsibilities towards sustainable objectives (Waas et al., 2011).

Sustainability assessments should pursue following objectives (Huge´ et al. 2011):

- information generation;
- forum for debate and deliberation;
- fostering attitude shifts;
- structuring complexity.

Waas et al. (2014) state that the main objective of sustainable assessment is to convey information and understanding for a more comprehensive evaluation in taking decisions at the level of policy makers. Authors confirm that if on the one hand the process of decision-making is certainly affected by scientific and analytic data, on the other hand, subjective aspects such values, ideology, interests play a relevant role being often the basis for the formation of diverging attitudes. The assessment of sustainability should be carried out in a specific context with the contribution of all stakeholders. In this way they have the possibility to gain knowledge of sustainability while learning information and for this reason shaping their attitude. Authors confirm that the process of information acquisition should underpin the implementation of sustainability assessment and deal with all the dimensions of the analysis. Therefore, indicators and multi-criteria decision-making approaches should play a major role. However, if the consideration of economic and environmental aspects may refer to several studies and data, a lack of an agreed definition of the concept of social sustainability is highlighted in the work of Ribeiro et al. (2011). Their conclusions confirm the results published by Carrera and Mack (2010) on the social aspect of sustainability and the indicators applied in this field.

Aiming to discuss the sustainability of nuclear energy, a review of documents published by international institutions such as the International Atomic Energy Agency (IAEA) and the Organisation for Economic Co-operation and Development/Nuclear Energy Agency (OECD/NEA) and articles in this field has been undertaken. Results are briefly resumed below.

If on the one hand, reports such as (NEA, 2000) discuss and recognize all the elements of sustainability, on the other hand, most of the IAEA's and NEA's reports show an approach to the assessment of sustainability that has remained quite stable across the documents reviewed. Reports such as (NEA, 2012a; NEA, 2013a; IAEA, 2006; IAEA, 2014b; IAEA, 2015b, IAEA, 2016) discuss the sustainability of nuclear energy according to a three-pillar model (economic, environmental, social/institutional) focusing on natural uranium resources, impacts on human health, costs of generation and financing issues, radioactive waste and proliferation issues. The approach is mostly technical-economic and conveys a positive image of nuclear energy where for example severe accidents are considered good opportunities to improve safety performance. In (IAEA, 2016) this approach is mostly confirmed but the issue of radioactive waste is acknowledged to represent an intergenerational issue. Normative and ethical aspects are also mentioned in the analysis of social acceptance.

The IAEA has developed within the framework of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) a well-recognized approach for the assessment of nuclear energy sustainability (IAEA, 2008a; INPRO, 2016). A discussion of the basic principles employed in the INPRO methodology has suggested an underrepresentation of aspects mainly related to the equity and normativity principles. Further remarks have been obtained on an incomplete inclusion of the dynamic principle in the methodology.

In the open literature efforts are seen to refine concepts and methodologies for the assessment of nuclear energy sustainability. Adamantiades and Kessides (2009) consider many of the topics discussed in aforementioned reports, however giving a more relevant role to issues such as public attitude and long-term management of radioactive waste that could represent serious limiting factors for the development of nuclear energy. According to Piera (2010) social and political/institutional issues should be included in the assessment. These topics together with waste management, natural uranium resources and non-proliferation should underpin any assessment of nuclear energy sustainability. Stamford and Azapagic (2011) compile a list of 43 indicators based on a life cycle approach and agreed with experts. Applications of this methodology are presented in (Santoyo-Castelazo and Azapagic, 2014; Stamford and Azapagic, 2014).

Laes et al. (2011a) discuss the evaluation of external costs in the case of severe nuclear accident. They point out the need for a deeper assessment of outcomes and procedures applied in safety. In a case study presented in this article, the initial assumptions have been discussed by experts in the field.

Eggermont and Hugé (2011), based on a historical review of the approaches applied in nuclear decision-making, underline some weak aspects such as the lack of integration in society (e.g., lack of a coherent siting policy, accidents risks). Authors highlight the intergenerational aspects inherent in the use of nuclear energy (e.g., management of radioactive waste). They also note the non-application of the precautionary principle and the low integration of stakeholders' views in the process of decision-making.

Stein (2013) presents an assessment where the sustainability of electricity generating technologies including nuclear energy is discussed. The analysis was performed by means of the Analytic Hierarchy Process (AHP) and its generalization Analytic Network Process (ANP).

Verbruggen et al. (2014) focus their analysis on the sustainability frameworks developed by the IAEA and IEA. They point out that both methodologies skip aspects fundamental for a sustainable development. The IAEA methodology offers the best practice for a responsible use of nuclear energy especially for countries that intend to introduce this energy but face infrastructure limitations such as in the case of developing countries. Risks of nuclear energy are not accounted in the IEA's approach. Authors propose 19 indicators grouped in five dimensions: environment, economics, risks, social, and governance. Based on this approach, authors cast doubt on the sustainability of nuclear energy. According to Verbruggen and Laes (2015) nuclear energy is characterized by socio-political tensions and polarization within and across countries that could undermine the democratic debate that is considered vital for a proper governance towards sustainable objectives. They point out that the IAEA's methodology misses to account for some moral and ethical aspects such as the burden of radioactive waste (intergenerational equity), the application of precautionary principle for a technology prone to severe accidents, the fact that most countries cannot attain best practices in nuclear technologies (intra-generational equity).

The analysis of the roles of public opinion and political support in the INPRO methodology confirms that a techno-economic approach is mostly dominant (Calabrese, 2014). Banerjee and Bonnefous (2011) in their study on an important nuclear company (AREVA) conclude that sustainability strategies developed and implemented through stakeholders management tend to be driven by economic criteria while environmental and social sustainability remain mainly symbolic gestures. At the operational level, their findings do not indicate any significant change in practice from a business as usual approach: economic and profit motives continued to dominate decision making on environmental issues. In their analysis, environmental initiatives were invariably evaluated using traditional criteria: cost reductions, efficiency gains, and customer preferences.

Cartelle Barros et al. (2015) assess the sustainability of 10 technologies for electricity generation based on 27 indicators in the economic, social, and environmental fields by means of MIVES.

Grafakos et al. (2015) present an example of integration of stakeholders in decision-making. Authors focus their study on local communities through the use of Multiple Criteria Analysis (MCA). Štreimikienė et al. (2016) present an assessment of the Lithuanian power sector. The authors consider 6 energy sources and employ 20 indicators discussed by means of the Analytic Hierarchy Process (AHP). Weights assigned to each indicator have been determined in compliance with the indications of 25 experts. Gralla et al. (2016) summarize the facets of sustainability embedded in reports that describe the national energy strategy of 9 nuclear countries. They analyse this type of information considering 56 indicators used for the assessment of sustainability. The article shows that topics such as social risks and intergenerational issues (radioactive waste) are underrepresented. Authors note that poor information regarding the involvement of stakeholders and the data used in the development of reports is generally provided to the reader. In addition, the concept of sustainability is rarely clearly stated.

This brief summary confirms that the scientific investigation on the concept of sustainable development is ongoing and has produced a series of results on principles and meanings of this concept. Research has devoted significant efforts to identify objectives and methodologies for a proper assessment of sustainability. However, the development is still under way concerning the choice of criteria, methods, and tools. The assessment of sustainability should be strictly linked to decision making. Despite this fact, very few applications have been reported in the literature and therefore, insufficient for a proper validation of the procedures proposed by researchers.

Equity and integration principle are often recalled and applied in the assessment of sustainability. The participation of stakeholders and experts is relevant in most of reviewed studies to improve the robustness of initial assumptions and therefore of outcomes. In general, the social dimension of sustainability has not reached an agreed definition and is less developed in assessments. The integration of economic objectives with environmental and especially social ones appears to be still unsatisfactory where the cultural dominance of more traditional approaches makes complex a balanced consideration of all dimensions of sustainability.

These difficulties are even more pronounced in the assessment of nuclear energy sustainability. Notwithstanding recurring criticism regarding the compliance of the methodologies proposed by the IAEA and the IEA, these approaches have not been refined in the meanwhile. Intergenerational and intra-generational issues are mentioned in their reports but they apparently do not have the role usually assigned in the literature (e.g., IAEA, 2016). The participation of stakeholders is simply mentioned or even not indicated in these general reports. The precaution principle is not discussed as well. In addition, disagreements are seen in the approach to safety, severe accident risks, and long-term management of radioactive waste.

As aforementioned, an evaluation of the basic principles employed in the INPRO methodology has suggested an underrepresentation of aspects mainly related to the equity and normativity principles. This analysis has also revealed an insufficient consideration of the dynamic principle. The analysis of alternative patterns of development is set outside the methodology in a more general view whose constraints are not directly used for the assessment substituted by acceptance limits set internally.

No article has been found in the literature answering the questions raised in aforementioned studies. Institutional mission, constraints to changes and cultural difficulties seem to have prevented an effective integration of the IAEA's methodology with more recent results on sustainability assessment. A techno-economic approach appears to be still dominant where economic objectives are prone to jeopardize alternative targets.

The INPRO methodology has a fixed structure with a plain consideration of all indicators and areas of investigation. The methodology is composed of a fixed hierarchy of requirements mostly referring to analytical quantities or mutually excluding judgments (Yes/No). Non-quantitative criteria, the consideration of public opinion and political support, the role of local communities and in general of stakeholders seem to have been implemented without a sufficient compliance with the principles identified in the literature. The risk that economic or political reasons could bias the outcomes of assessments is still present if we consider the core business of the IAEA that is to promote the pacific use of nuclear energy especially in developing countries (newcomers). This risk could also be suggested by the type of assessor considered in the methodology that could either be a technology user (client) or a technology developer (seller).

Moving from these considerations the document proposes a methodology for the assessment of nuclear energy that could integrate the IAEA's approach and its deep techno-economic knowledge of the technology within a structure more consistent with the principles that should underpin a sustainable development and its assessment.

A wider consideration of the equity principle would require to include in the assessment a series of items identified in the literature. Stakeholders should play a more relevant role in decision-making. In this view attitudes of the public opinion or the viewpoint of local communities should be properly taken into account to achieve a fair distribution of burdens and benefits. In this regard the study of Scott et al. (2011) clearly points out this requirement in the analysis of the water-energy nexus.

The integration principle would require the consideration of multi-criteria decision-making methodologies and tools to permit the use of quantitative and non-quantitative criteria as required by the normativity principle.

A closer consideration of nuclear with competing technologies could enhance the robustness of evaluations with a more consistent compliance with the dynamic principle. With these premises, the performance of each technology in quantitative and non-quantitative criteria could be properly taken into account in the assessment.

A set of indicators consistent with the approach of the IAEA confirms the link of the proposed layout with the INPRO methodology.

In order to consider normative aspects and values not only in the initial part but also in the concluding part of the assessment, the outcomes of the assessment of proposed scenarios is performed by means of a MCDM tool. This choice introduces a novel element in the assessment where specific group of indicators could be more attractive in the viewpoints of stakeholders or others indicators should play a minor role for example in the case of high uncertainties in their determination (precaution principle).

The proposal presented in this study considers the following question: "How can we fill the gap seen between the advances of theoretical research on the concept of sustainability and the state-of-the-art of the IAEA's methodology for the assessment of nuclear energy sustainability?".

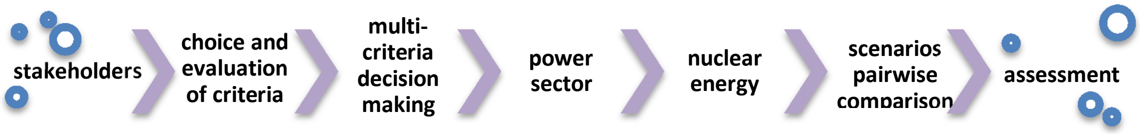


Figure 1.1: Schema of the methodology proposed in this study

In each step of the framework different tools have been employed to fulfill intermediate objectives.

The MCDM method adopted in the analysis is based on the Analytic Network Process (ANP). The tool employed for the purpose is Super Decisions (*stakeholders*, *multi-criteria decision-making,* and *assessment* steps in Fig. 1.1).

NEST (Nuclear Economics Support Tool) has been applied for the determination of economic parameters (*choice and evaluation of criteria* in Fig. 1.1). LEAP (Long-range Energy Alternatives Planning) has been used for the analysis of the power sector (*power sector* in Fig. 1.1). DESAE (Dynamic Energy System – Atomic Energy) is the tool employed for the determination of quantities specific of the nuclear fuel cycle (*nuclear energy* step in Fig. 1.1).

The GAINS project has been conceived in the frame of the INPRO methodology (IAEA, 2013b). One of its outcomes is the so-called “GAINS Framework”. This tool is a subset of the INPRO indicators that permits to catch most important requirements of the methodology (IAEA, 2013b; Kuznetsov et al., 2013). This result was the starting point for the definition of the indicators applied for the assessment of nuclear energy sustainability (*nuclear energy* and *scenarios pairwise comparison* steps in Fig. 1.1).

Chapter 2 presents a review of the literature on the concept of sustainable development and sustainability assessment. The focus of the second part of the chapter is on nuclear energy sustainability. In the final part of the chapter an analysis of the basic principles of the INPRO methodology is presented. Chapter 3 presents the methodology together with a brief description of each tool and its applications published in the literature. Chapter 4 resumes the techno-economic modeling of technologies that have been developed according to the indications of updated references listed at the end of the chapter. Chapter 5 resumes the activities performed for verification purpose. In chapter 6 a complete application is presented.

2. SUSTAINABILITY ASSESSMENT AND NUCLEAR ENERGY

2.1 Sustainable development and sustainability assessment

The concept of sustainable development (SD) has become one of the most important issues debated by the scientific community and policy-makers. Concerns on climate change, social and geographical inequalities, scarcity of natural resources have pointed out the urgent need for a U-turn of a concept of development simply based on economic considerations.

This term was first used in 1731 by Hannss Carl von Carlowitz in his publication on sustainable forestry (Waas et al., 2011). The growth seen in population, economic needs and better knowledge of the environment contributed to increase the awareness that decoupling development and environment will lead to dramatic effects especially for future generations (Waas et al., 2011). Following a period of incubation, major achievements in the definition of SD have been registered in the years from 1987 to 1995. Key milestones of this development are the publication of the *Our Common Future* report (WCED, 1987) and the United Nations Conference on Environment and Development held in Rio de Janeiro, in 1992.

Waas et al. (2011) affirm that *Our Common Future* is fundamental for several reasons: launched a definition of sustainable development; affirmed that sustainable development is a substantial component of the international development thinking and practice; signed the beginning of an impressive increase in works on this theme that contributed significantly to its popularization. The Conference in Rio expressed 27 principles for a sustainable development and adopted the AGENDA 21 for a global action plan towards sustainability.

In *Our Common Future* it is found the well-known definition: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. Two key concepts are pointed out:

- the concept of ‘needs’, in particular the essential needs of the world’s poor to which overriding priority should be given;
- the idea of limitations imposed by the state of technology and social organization on the environment’s ability to meet present and future needs.

This definition assigns priority to the needs of large majority of people living in poverty as a consequence of the social organization and state of technology. Environmental protection is a prerequisite for a sustainable development as a moral obligation towards other living beings and future generations (WCED, 1987). The following statement is a more operational definition of sustainable development: “In essence, sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations.” (WCED, 1987).

Based on these definitions, in *Our Common Future* eight objectives for a sustainable development are proposed: (1) reviewing growth; (2) changing the quality of growth; (3) meeting essential needs for job, food, energy, water, and sanitation; (4) ensuring a sustainable level of population; (5) conserving and enhancing the resource base; (6) reorienting technology and managing risk; (7) merging environment and economics in decision-making; and (8) reorienting international economic relations.

One of the consequences of these objectives is for example the stabilization of population growth according to the rate of changing capacity of the environment. Walls et al. (2011) highlight that this report has a revolutionary approach when it couples development and environment as well as a reformist approach when maintains the central role of development seen as a mean to improve living standards and to reduce poverty.

The authors present other important achievements in the definition of SD that should entail:

- normativity principle;
- equity principle;
- integration principle;
- dynamism principle.

The first principle states that the concept of SD depends entirely on the views and values on which the interpretation of sustainability has been formed and on the decision of which kind of legacy we want to leave to future generations. This principle affirms that scientific and rational approaches are in general not sufficient where normative/subjective aspects should play a proper role for the interpretation and determination of what is a sustainable development. The onset of a dichotomy between techno-economic analysis and a more general and non-quantitative approach is envisaged and confirmed later on. Equity is the second pillar underpinning the concept of sustainable development. This principle encompasses many-fold interpretations: intra-generational equity, intergenerational, geographical (local vs. global). Procedural aspects are also essential to assure the democratic participations and transparency of information. The integration principle requires that traditional development objectives should be harmonized with more recent and well-recognized environmental and social issues in a process of change directed towards sustainability. The dynamism principle considers that sustainable development is a process of change where alternative patterns should be evaluated.

Authors remind the need to include uncertainties by adopting a precaution approach that avoids even poorly understood risks of serious or irreversible damages; to design for surprise; to manage for adaptation. This implies acting on incomplete but suggestive information where social and environmental systems are at risk (Waas et al., 2011). However, they also point out that “although reasonable in theory, in practice it seems to be overly ambitious and unrealistic to realize positive results for all sustainability objectives and principles at the same time in every instance”. Authors argue the need for a new governance of this process of change where all stakeholders play a role in decision-making through different manners of democratic participation and a share of responsibilities towards sustainable objectives. Governance should be capable to transform itself according to the evolution of the relationship between development and environment that is unpredictable and uncertain (Waas et al., 2011).

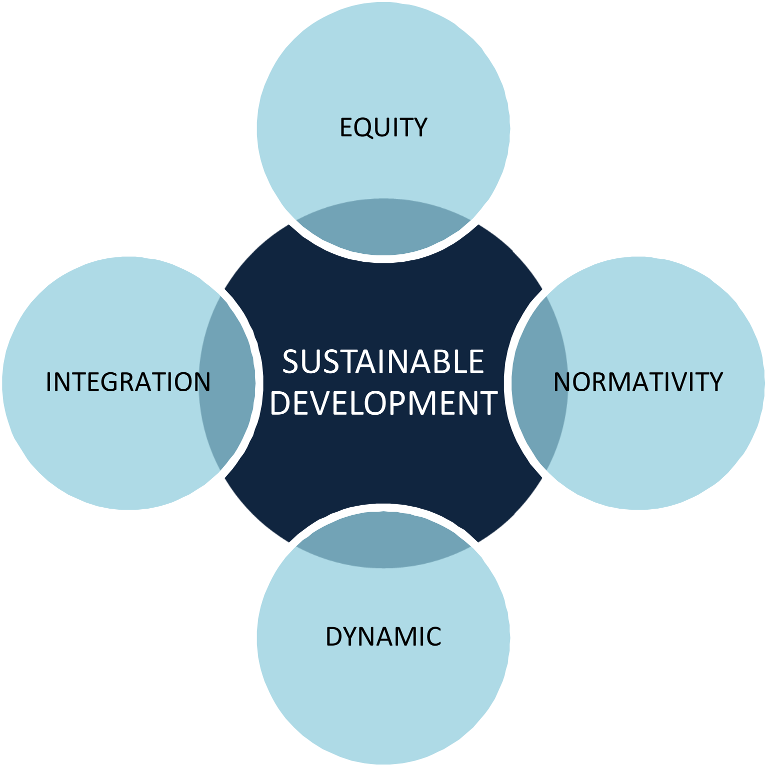


Figure 2.1: Principles of sustainable development

The report (OECD, 2007) gives a general overview of the vision of the OECD regarding the relationship between energy and sustainable development. Energy should be available, affordable, secure, and reliable. Energy resources should be environmental-friendly and useful to meet sustainable development objectives. The social dimension of SD lies, besides energy security, in a series of social norms and individual behaviors especially in the end-use sector This document endorses the indications of the Agenda 21 for a proper governance of SD policies: central role of intergenerational issues; need for analysis and assessment; participation of all stakeholders; use of indicators and targets to monitor status and trajectory of development. Nuclear energy is judged a mature and nearly carbon-free technology that could properly meet energy security objectives (OECD, 2007). Three main topics could represent an obstacle for the development of nuclear energy: lack of political stability and stable regulatory frameworks that could lead to an increase in investment risks; public opposition due to perceived threats mostly related to radioactive waste and nuclear accidents; proliferation risks. The lack in consensus due to the topic of radioactive waste is explained mostly through ethical considerations where perceived risks outweigh actual risks.

Assefa and Frostell (2007) study the social sustainability of decisions in energy policy. They adopt three indicators: knowledge, perception, and fear according to an approach inspired by the social impact assessment (SIA). The quantitative evaluations presented in the article have been obtained through a questionnaire sent to laypeople randomly selected.

Carrera and Mack (2010) review the indicators employed for the assessment of social sustainability. They identify 1320 parameters later on reduced to 26 through the application of quality criteria. Some overarching criteria have been identified: continuity of energy service over time, political stability and legitimacy, social components of risk, quality of life. Carrera and Mack (2010) assess the indicators through the judgments of European stakeholders by means of a Delphi approach. In the initial subset 20 of 26 indicators proved to be applicable and reliable through the determinations of institutional database and experts' interviews. In addition, this article provides the results of an assessment of 7 electricity generating plants evaluated by means of 9 indicators. Small-scale plants showed to be preferable in comparison with large-scale plants mostly because of criteria dealing with risk and public acceptance. Carrera and Mack (2010) are confident that the application of different methodologies increases the robustness of assessment and confirm that public attitudes should be assessed through large scale surveys.

Ribeiro et al. (2011) discuss the concept of social sustainability by considering the indicators applied in the literature. Authors affirm that this concept has not reached a unique and agreed definition. Differently from environmental issues, no institutional constraints or indications have been identified in the social dimension. They conclude that this concept is truly multi-dimensional and close to a general concept of "quality of life". They affirm that social acceptance and risk factors are fundamental in assessing the social dimension of sustainability. Authors highlight that an unequal distribution of impacts reinforces a NIMBY behavior even in the case of renewables. The article provides a list of social indicators that should be determined through institutional sources or by means of direct evaluations (e.g., through experts' interviews).

Huge´ et al. (2011) indicate a series of principles for a sustainable development:

- global responsibility;
- integration;
- inter and intra-generational equity;
- precaution;
- participation.

The precautionary principle addresses the need to not postpone actions to mitigate the degradation of environment even if the scientific demonstration is still uncertain. These same principles should pervade the assessment of sustainability where undesirable trade-offs should be avoided. Based on these principles, indicators then permit to make proper evaluations and to move towards the decision-making level. It is worth reminding that the authors clearly state that the exclusion of some principles in the assessment could hide the assessor's attempt to bias results (Huge´ et al., 2011).

Impacts assessments should pursue following objectives:

- information generation;
- forum for debate and deliberation;

- fostering attitude shifts;
- structuring complexity.

Meeting these objectives could help policy-makers in widening their views through the consideration of alternative solutions and through the interpretation of complex challenges modelled into a manageable framework (Huge´ et al., 2011). Nonetheless, each case study may bring different results depending on the choice of criteria and indicators. In the evaluation of nuclear energy sustainability normative viewpoints and the emphasis on different principles may lead to clearly diverging conclusions. The respect of all principles should be assured not only in the analysis but also in the procedures and processes adopted for the assessment (Huge´ et al. 2011).

Laes et al. (2011b) present a methodology to integrate traditional approaches mostly based on experts' evaluations with multiple rational positions and different perspectives within a Belgian context. In particular, authors describe a novel approach to develop scenarios where stakeholders and experts are coordinated to determine key parameters and inputs. The aggregation of results is carried out according to the principles of sustainability through the use of a MCDM tool based on a fuzzy logic approach (Laes et al., 2011b).

Waas et al. (2014) affirm that the main objective of sustainability assessment is to convey information and understanding for a more comprehensive evaluation in taking decisions at the level of policy-makers. They point out that the gap between discourses on sustainable development and practical applications remains large. Authors agree on the fact that if on the one hand the process of decision-making is certainly affected by scientific and analytic data, on the other hand, subjective aspects such as values, ideologies, and interests play a relevant role being often the basis for the formation of diverging attitudes among the stakeholders (Waas et al., 2014). To be effective at the level of decision-making, the concept of sustainable development should be properly interpreted according to its basic principles. Its inherent multidimensional nature should be structured in an operational framework. They confirm that this requirement should be fulfilled through the use of indicators and indices to form a consistent and manageable tool. Sustainability assessment stands as a new practice still under development (Waas et al., 2014). However, the authors identify four objectives that SA should pursue:

- information generation for decision-making;
- operationalization and forum for participation, debate and deliberation;
- social learning;
- structuring the complexity.

The assessment of sustainability should be carried out in specific contexts with the contribution of stakeholders that gain knowledge of this concept and learn information shaping their attitude. A process of information acquisition should underpin the implementation of SA across the dimensions of the analysis. Indicators and multi-criteria decision-making approaches should play a major role.

2.2 Sustainability and nuclear energy

The concept of sustainable development and nuclear energy sustainability are discussed in (NEA, 2000). The indications contained in *Our Common Future* are endorsed in the report through a multi-dimensional approach to sustainable development. Social and environmental dimensions are considered especially focusing on the impacts on human health and environment induced by the use of nuclear energy. The equity principle is judged a fundamental for a sustainable development. Therefore, OECD nations as self-interest and global responsibility should provide co-operation, funds and technologies to developing countries. It is reaffirmed that both the precaution and participation principles should be applied. The Nuclear Energy Agency is confident that explorations will be capable to meet the need for primary energy supplies without limitations to development. All principles of SD are taken into account and judged fundamental for decision-makers (NEA, 2000).

These premises encompass the need for a multi-criteria analysis whose development should be reinforced. In agreement with these indications, the report presents several aspects of nuclear energy sustainability and proposes 9 indicators for its assessment. Nuclear energy is capable to improve security and efficiency of the power sector thanks to a more ample offer of energy sources. Next generation reactors are expected to be cheaper, quicker to build, and easier to maintain. External costs and liabilities have been in great part accounted in the cost of nuclear generation as well as the cost of waste disposal and decommissioning not left to future generations (NEA, 2000). Research on severe accidents, uranium resources, and waste management will contribute to markedly ameliorate existing solutions. The negative attitude of public opinion whose opposition is judged nearly independent from the indications of experts, remains an open issue. In this view, the independence of regulatory bodies and a transparent and accurate information are pointed out as significant factors to overcome this limitation.

In (IAEA, 2006) nuclear energy is discussed in the frame of sustainable development through the consideration of its economic, environmental and social dimensions. Most relevant environmental impacts (radiation, air pollution, GHG emissions, and radioactive waste) are presented. It is stated that under normal operation the radiation hazard of nuclear plants is lower than in other technologies (e.g., coal) and well below the natural background. Severe accidents are presented as a good opportunity to gain essential information that could enhance safety. This confident position is also confirmed in the case of long-term radioactive waste management, a key issue in the debate between decision-makers and the public. It is highlighted that nuclear technology produces a small volume of waste in comparison for example with coal. However, technical solutions for storing, confining and monitoring radioactive waste are well-assessed and already available. Nevertheless, it is pointed out that there is no technical urgent need for deep geological disposals. In addition, the cost of the back-end of nuclear fuel cycle has been already internalized in the cost of electricity. The proliferation issue requires the reinforcement of controls especially in facilities for the enrichment and reprocessing of nuclear fuel. This issue, however representing a serious risk, is not strictly correlated to the development of nuclear energy (IAEA, 2006).

Adamantiades and Kessides (2009) note that several reasons foster the use of nuclear energy such as the diversification of energy sources and the reduction of fossil fuels imports. Beside these reasons, nuclear energy is capable to reduce the dependence on fuel price and GHG emissions. Authors report that significant improvements have been achieved in availability and regulatory issues while an expansion of expenditures in exploration has permitted to increase the amount of proven natural uranium resources. On the other hand, issues such as safety, waste management, and proliferation may heavily limit the opportunities offered by nuclear energy (Adamantiades and Kessides, 2009). Probability Safety Assessment (PSA) evaluations contradict the perception of the public regarding the risk of severe accidents in nuclear power plants. The authors point out that the Chernobyl accident that has certainly been a large-scale and severe accident, was not out of line in comparison with other serious industrial accidents. Comparative evaluations of the fatalities occurred during severe accidents say that nuclear is far less harmful than other power technologies. While authors judge the perception of risk mostly due to subjective reasons, the disposal of radioactive waste emerges as a crucial factor for the expansion of nuclear energy. Notwithstanding experts and scientists consider that reliable technical solutions for the long-term disposal of radioactive waste already exist, the opposition of the public opinion remains one of the most difficult issues in this field. Adamantiades and Kessides (2009) describe the risk of diversion rising in some processes of a nuclear fuel cycle (e.g., enrichment, reprocessing) and the actions undertaken by the international organizations to mitigate this risk. These initiatives are also fostered by the common interest of the USA and Russia to promote a peaceful use of nuclear energy. Even if proliferation is mostly a political issue, authors are confident that the multinational fuel banks could help in overcoming this obstacle to the development of nuclear energy.

Based on a life cycle approach, Stamford and Azapagic (2011) propose a SA framework composed of 43 indicators to analyze key techno-economic, environmental and social issues. This framework has been developed according to the viewpoints of different stakeholders. Interviews have been performed to determine the indications of stakeholders. Among the techno-economic indicators, authors include: technological lock-in, flexibility, immediacy (lead time), and incentives. The environmental dimension should be analyzed through 8 indicators typical of a life cycle approach. The indicators employed for the social dimension are: provision of employment, human health impacts, large accident risks, local community impacts, human rights and corruption, energy security, nuclear proliferation, and intergenerational equity. Several correlations and dependencies existing among the indicators make meaningful a classification according to the usual three-pillar model (Stamford and Azapagic, 2011).

The number of fatalities is the quantity used to evaluate the risk of severe accidents. Authors agree on the fact that the perception or psychologic attitude of the public opinion towards nuclear is mostly affected by severe accidents. At the time, the Chernobyl accident was the only event recorded in this category. Technologies characterized by a much lower probability of occurrence of disastrous accidents generally show a much higher frequency of less severe accidents. Climate change, abiotic resource depletion and long-lived hazardous waste are the intergenerational issues considered in this SA framework. Radioactive waste from nuclear power plants as well as CO_2 captured from fossil-fuelled plants are included in the category of long-lived hazardous waste (Stamford and Azapagic, 2011).

Rogner (2010) considers radioactive waste, proliferation, safety risks, trans-boundary consequences, and costs among the most relevant issues for the sustainability of nuclear energy. The author highlights the dichotomy between actual and perceived safety of nuclear technology. However, he is confident that innovations and investments will surely improve the safety records of nuclear energy. The author trust that if aforementioned issues are solved concerns of the public opinion about the use of nuclear energy will disappear. However, nuclear energy alone is not the solution to climate change. The author affirms that the volume of radioactive waste is small in comparison with other technologies and that a safe management is already available.

Laes et al. (2011a) discuss the evaluation of external costs in the case of severe nuclear accident. External costs of nuclear energy are usually assumed to be notably lower than fossil fuel technologies. However, the authors argue that the relationship low probability vs. high consequence typical in the case of nuclear should be assessed in more detail to account for the impact on risk perception and its social acceptability. A proper consideration of external costs should require that the operator is fully liable of all the consequences of a nuclear activity. In addition, the evaluation of risks should be performed by means of an approach such as that employed by insurances. Authors present a careful analysis based on the so-called pedigree assessment of the key assumptions used to determine the external costs in the case of severe accident in a Belgian nuclear power plant. Experts involved in the study note the underestimation of specific conditions as well as the need for a more detailed treatment of the effects of risk perception and non-radiation induced diseases. Overall, the article indicates some weak aspects in procedures and outcomes that should be properly modified for a correct governance of sustainable development.

Eggermont and Hugé (2011) discuss the role of nuclear energy within the Belgian transition to a sustainable energy sector. Based on a historical review of the approaches applied in nuclear decision-making, they note out some weak points such as the lack of integration in society (e.g., lack of a coherent siting policy, evaluation of accident risks). They also highlight some intergenerational aspects of nuclear energy (e.g., management of radioactive waste). In this view, the management of radioactive waste involves the topic of distributive justice or inter-generation equity in the consideration of regional realities. However, the authors affirm that this issue has not been technically solved. In a more ample evaluation of SD, the non-application of the precautionary principle and a low integration of stakeholders' views in the process of decision-making are limiting aspects as well. Eggermont and Hugé (2011) note that the evaluations performed by nuclear experts and nuclear institutions could be not truly independent because of their cultural difficulties in the transition towards a new paradigm of sustainability. Authors underline that Generation III reactors however evolutionary do not represent a true transition to a sustainable pathway. They claim that the use of uranium resources, large scale plants, severe accident risks and stakeholders participation do not satisfactory meet the principles underpinning SD.

Visschers and Siegrist (2012) discuss the effect of procedural and outcome fairness on the acceptance of decisions. The topic is the decision to rebuild nuclear power plants. Fairness of decision is certainly more important than procedural fairness in the public's acceptance. Fairness of outcomes, general attitudes, and perceived benefits are all important to determine the laypeople's attitude.

In (NEA, 2012a) a detailed analysis of the role of nuclear energy is proposed. Based on a cost-effective approach and pursuing the objective to limit GHG emissions, it is affirmed that nuclear energy should be deployed at a significant rate in coming decades. The financing capability is one of the most important obstacles to its development being nuclear a capital-intensive technology. This is especially true in the case of private investors. The report outlines main concerns that could undermine a significant development of nuclear energy: adequate industrial infrastructure, availability of uranium resources, management of radioactive waste, public acceptance. Large part of the society is skeptical towards nuclear as drawbacks are recognized to be largely overriding benefits. Aspects such as safety and radioactive waste management, besides the issue of proliferation play a relevant role to determine this attitude. These factors are discussed in the NEA's report without the adoption of a three-pillar model. None of these aspects is judged to be insurmountable factors for the deployment of nuclear at the level required to meet the objective to reduce emissions. However, it is clearly affirmed that a change in policy towards 2020 is necessary. Any further delay could cast doubts on the occurrence of the conditions necessary for a sustainable development of nuclear energy (NEA, 2012a). The study confirms that governments and utilities are mostly responsible for the adoption of the decisions necessary to overcome the challenges encountered if a significant growth of nuclear energy is planned. Natural gas resources could limit the competitiveness of nuclear energy wile a positive integration of nuclear with renewables could be a competitive advantage.

Stein (2013) presents a sustainability assessment performed by means of the Analytic Hierarchy Process (AHP) and its generalization Analytic Network Process (ANP). This study deals with 9 technologies for electricity generation. The discussion entails 7 indicators grouped in 4 clusters. Scenarios are proposed through a proper adjustment of clusters' weights (Stein, 2013).

The OECD/Nuclear Energy Agency published a report on the transition from an open fuel cycle to a closed fuel cycle (NEA, 2013a). The report deals with two key factors for sustainability: natural uranium resources and radioactive waste management. The document presents a heterogeneous analysis that takes into account the different level of economic development of the countries included in the study. Each group of countries is characterized by different types of nuclear fuel cycle in a synergistic approach to achieve an optimal use of natural resources and fuel cycle infrastructures.

In (IAEA, 2014b) it is reaffirmed that nuclear is an energy source capable to meet sustainable development goals, in particular energy security and environmental targets.

Verbruggen et al. (2014) focused their analysis on the sustainability frameworks developed by the IAEA and IEA. They note that the IAEA's methodology skips aspects fundamental for a sustainable development. Instead, the authors judge this methodology aimed to offer the best practice for a responsible use of nuclear energy. Notwithstanding the IEA's approach considers issues such as radioactive waste and public acceptance, judged weak points for the deployment of nuclear energy, it neglects aspects such as the risks of nuclear energy. Based on these considerations the authors propose a list of 19 indicators grouped in 5 dimensions: environment, economics, risks, social, and governance. Nuclear energy could represent an obstacle to the deployment of renewables and the increase in efficiency by end users that the authors argue being master solutions to tackle the environmental concerns. Subsidies to nuclear, its high costs, and the competition with renewables to meet base load could all be potential factors delaying the transition to a really sustainable power sector (Verbruggen et al., 2014). Authors judge nuclear energy unsustainable because of its low adaptation to climate change and its incomplete accounting of costs that are delivered to society and not to the owner or to the operator. In the article issues such as the limitation of natural resources, and proliferation risks are recalled. It is pointed out that nuclear technology is not affordable for most countries. Authors judge nuclear as a risky and increasingly costly technology prone to the action of lobbies that do not take properly into account the public opinion (Verbruggen et al., 2014).

Santoyo-Castelazo and Azapagic (2014) present a framework for the assessment of sustainability based on a life cycle approach. Criteria are classified according to the three dimensions of sustainability and studied by means of a multi-criteria decision-making methodology. Authors present a case study on the energy sector of Mexico.

The indicators defined in (Stamford and Azapagic, 2011) have been applied in the study reported in (Stamford and Azapagic, 2014).

Verbruggen and Laes (2015) acknowledge that renewables and nuclear compete to mitigate the impact of CO_2 emissions on climate. However, they point out that this aspect is not the only fact to take into account in the analysis of nuclear energy sustainability. For this purpose, they discuss the sustainability assessment frameworks of the IAEA and IPCC. Nuclear energy is characterized by socio-political tensions and polarization within and across countries that could undermine the democratic debate that is considered vital for a governance capable of pursuing sustainable objectives (Verbruggen and Laes, 2015). They remind that even an expert analysis could be prone to biases due to ideological and political reasons so that a rationale and scientific approach could limit the opportunity to discuss sustainability visions in a more ample range of options and solutions. A biased choice of indicators in compliance with specific ideological positions could undermine the reliability of results. Authors confirm their analysis of the IAEA's methodology in which some moral and ethical aspects are not taken in due account such as the burden of radioactive waste (intergenerational equity), the application of the precautionary principle for a technology prone to severe accidents, the fact that most countries cannot attain best practices in nuclear technologies (intra-generation equity). Regarding the IPCC framework, Verbruggen and Laes (2015) underline that all the information and decision processes are established within nuclear institutions with a partial review or consideration of different viewpoints.

The article by Cartelle Barros et al. (2015) presents a review of MCDM methods and tools. The authors assess the sustainability of 10 technologies for electricity generation by considering 27 indicators in the economic, social, and environmental dimensions. For the purpose, they used the MIVES code. Environmental impacts are described by means of a life cycle approach where the values of indicators change cross the plant lifetime. In their sensitivity analysis nuclear energy achieves priorities lower than renewables but higher than fossil fuel power plants.

The capability of nuclear energy to reduce GHG emissions and poverty are the main reasons to support its expansion (IAEA, 2015b). Nuclear energy represents an opportunity to offer access to electricity services in developing countries. Among its key benefits, the IAEA indicates the reduction of airborne pollutants that cause the acidification of rains or the depletion of the ozone layer in the atmosphere. These specific characteristics permit nuclear energy to achieve external costs estimations well below those of fossil fuels even considering the effect of severe accidents such as Chernobyl and Fukushima. The report confirms that the dose to the public of nuclear energy under normal conditions is of the same order of magnitude of the terrestrial background. This statement is also valid for the dose due to the Fukushima accident (IAEA, 2015b). Improvements in safety in the aftermath of the Fukushima accident are reviewed and technical achievements in the area of radioactive waste disposal are presented. The deep geological disposal emerges as the final solution to prevent the interaction of radioactive waste with the environment by means of engineered and natural barriers. In this section a mention to the intergenerational equity is found but it is considered mostly an ethical topic not interfering with the assessment of sustainability. Improvements in technology suggest that high level waste should be retrievable to leave open the possibility to recover fissile materials in the future (IAEA, 2015b). In the document it is reaffirmed that the attitude of public opinion is a relevant issue pointing out that results of surveys may vary noticeably depending on how questions are framed. Therefore, the report warns that a due attention should be given to assess the quality and reliability of published results. However, it is confirmed that a recovery of a positive attitude towards nuclear energy has occurred if compared to the pre-Fukushima indications. India and the USA are accounted for values around 70% in favor of nuclear energy. Most of newcomer countries are aligned around this level of acceptance. Surveys presented in the report confirm that energy independence and climate change tackling are considered key benefits of a nuclear option.

The article by Grafakos et al., (2015) gives an example of integration of stakeholders in the process of decision-making. The focus of this study is on local communities. Authors apply a Multiple Criteria Analysis (MCA). Based on the consideration that different geographical and jurisdictional levels lead to select different criteria and therefore different outcomes, the article presents a methodology for the inclusion of stakeholders' preferences in the energy sector at the European level. The choice of criteria is based on the indications of involved stakeholders that play also a relevant role in the definition of weights and clustering of criteria.

Reese and Jacob (2015) discuss the concept of environmental justice intended as a series of actions aimed to achieve a fair distribution of environmental burden and benefits. Distribution is linked to the participation (role of affected subjects in decisions-making) and recognition (i.e., recognizing and acknowledging actor's and affected person's individual backgrounds). Authors mention the intergenerational justice pointing out that future generations could be seen as stakeholders that deserve adequate recognition. These themes are closely related to the concept of sustainable development and the moral/ethic basis recalled in several studies.

Štreimikienė et al. (2016) present a sustainability assessment of the Lithuanian power sector. They consider 6 energy sources and employ 20 indicators. The analysis has been conducted by means of the Analytic Hierarchy Process (AHP) where the determination of the weights employed in calculations has been done based on the indications of 25 experts. In their analysis nuclear energy showed the highest priority. The concluding remarks have been obtained by means of the Additive Ratio Assessment (ARAS).

Gralla et al. (2016) summarize the facets of sustainability embedded in the official documents describing the national energy strategy of 9 nuclear countries. They analyse these documents with respect to 56 indicators used for the assessment of sustainability. Authors note that the concept of sustainability is not clearly defined in most of the documents. The article shows that topics such as social risks and intergenerational issues (radioactive waste) are underrepresented. Poor information is given regarding the involvement of different stakeholders and the data used for the analyses presented in these documents. Authors agree with (Verbruggen and Laes, 2015) on the need for an independent authority that could provide clearly defined sustainability criteria based on a normative foundation.

The sustainability of nuclear energy is discussed in (IAEA, 2016) moves from the 17 Sustainable Development Goals (SDGs) recently expressed by the Unite Nations. The new goals indicated by the UN aim to shift the world towards a sustainable path where environmental sustainability, social inclusion and economic development are equally valued. This document recalls that nuclear power sustainability has generated substantial controversy mainly because of concerns about the risk of severe accidents and radioactive waste. The document maintains a traditional approach trough an analysis of sustainable development entailing three pillars: economic, environmental and social dimensions. The economic dimension is focused especially on the availability of natural uranium resources, EROI (energy returned on invested), and generation costs. If on the one hand it is affirmed that fissile resources of uranium (and thorium) are plentiful and not being a limitation to the sustainability of nuclear energy, on the other hand the consideration of grid connection, balancing systems and external costs give to nuclear energy competitive advantages. However, it is underlined that financing the construction of a nuclear power plant represents a unique challenge due to its high overnight cost. Nuclear energy is considered secure with stable price, reliable, policy resilient (carbon cost initiatives). In addition, nuclear has relevant capabilities to reduce the geopolitical risks due to the disruption of energy supplies that could occur outside the borders especially in the lack of domestic energy resources.

With regard to the environmental dimension of nuclear power it is reaffirmed that this low carbon technology will be fundamental in putting the world on an ambitious mitigation pathway. Parameters based on a life cycle approach (e.g., abiotic resource depletion potential, eutrophication potential) confirm that nuclear energy has a low impact on the environment. It is confirmed that safety and isolation of high level waste can be assured in stable geological formations combined with multiple engineered barriers. The use of nuclear for desalination and generation of potable water is presented as an application that could nicely meet sustainability objectives. The discussion of the social dimension is centred on the effects on human health and employment. In this regard it is said that the use of nuclear power induces impacts on human health that are lower than fossil fuel generation and comparable to those of renewable energy sources. Positive indications are also reported on employment levels and people relocation (in comparison with hydro).

In the concluding part of the (IAEA, 2016) the issue of intergenerational equity linked to the management of radioactive waste is discussed and acknowledged. The IAEA affirms that current generations are responsible to identify and develop sustainable and long-term disposal solutions. Public acceptance is another crucial point for the development of nuclear energy. Despite the fact that its benefits are fairly consistent with a sustainable development, the expansion of nuclear energy might be severely constrained in the absence of public support. It is acknowledged that the social acceptance of risky technologies depends not only on scientific evaluations but also on perceived risks and perceived benefits. Perceived risks depend on a series of individual and societal factors quite far from the analytical approaches used to determine the probability of death. Psychological factors such as dread and unknown risks, moral aspects, fairness and trust all play an important role in supporting or opposing nuclear technologies.

2.3 Analysis of the Basic Principles employed in the INPRO methodology

The INPRO methodology moves from the concept of sustainable development endorsed by the United Nations (INPRO, 2008a). The aim of a sustainable development is to achieve equity within and across countries as well as across generations by integrating growth, environmental protection and social welfare. Sustainability is considered from four correlated but distinct viewpoints or dimensions: economic, environmental, social, and institutional. The objective of the INPRO methodology is to establish with confidence the potential of innovative nuclear systems to contribute to sustainable energy supply and hence, to meeting the general objective of sustainable development (INPRO, 2008a).

The key issues for a sustainable energy supply are: economic performance, energy consumption, energy intensities, and efficiency of energy distribution and use. The environmental dimension is focused on following topics: climate change, air pollution, water pollution, solid and radioactive waste, energy resources, land use, and deforestation. With regard to the social dimension, main topics of interest in are: energy affordability, accessibility and disparity, employment generation, public participation in decision-making, energy security, proliferation threats, and safety of energy systems (INPRO, 2008a). The institutional dimension concerns following items: national sustainable energy strategy, international cooperation on energy, energy legislation and regulatory framework, energy science and technology, and energy accident preparedness and response measures (IAEA, 2008a).

The basic principles employed in the INPRO methodology are resumed in Tab. 2.1 and Tab. 2.2. A system or a part of it is sustainable when all users' requirements and criteria are fulfilled. By consequence, this condition fulfills all the requirements expressed in the basic principles. Tables report the corresponding INPRO area and most relevant dimensions of sustainability. This latter indication has been determined in agreement with the classification reported in previous paragraph.

In addition, each basic principle has been correlated to one or more of the principles discussed in the literature (integration, normativity, dynamic, equity). According to the dynamic principle, a sustainable development is a process of change where alternative options are considered. The equity principle considers a fair distribution of benefits and burdens. The integration principle pursues the harmonization of traditional objectives with environmental and social objectives. The normativity principle considers that norms and rules adopted for a sustainable development are strongly linked to beliefs and values of individuals.

Basic principles in the economic and infrastructure areas have been intended mainly to overcome inequalities and therefore pursuing inter-generational equity objectives. The basic principles of waste management aim to protect environment and human health so that intra-generational and intergenerational issues are addressed. Integration objectives are pursued as well. Proliferation resistance aims to integrate additional objectives with respect to economic targets so that integration is prominent, however, the prevention of diversion risks protects groups of people or countries not using nuclear technologies (intra-generational issues). The physical protection area addresses mostly integration and at a lesser extent intra-generational issues (equity of exposures across different groups of people).

The basic principles of the environmental area of INPRO point out mainly the integration of environmental objectives and the preservation of the environment and nonrenewable resources for future generations (intergenerational equity). Safety principles BP1, BP2, BP3 could be intended as an integration of safety objectives with traditional objectives. However, safety initiatives could also be interpreted as a way to avoid people living in the near-by of power plants to be exposed to risks higher than groups living far away. Trans-boundary effects are also addressed. In this view, intra-generational equity objectives could be identified. Principle BP4 in the safety area is consistent with the dynamic principle, where research is necessary to look for or prove alternative solutions on a sound knowledge.

Results of this analysis suggest that integration and equity principles are fairly well considered in the methodology. The equity principle deals mostly with intra-generational and intergenerational issues while less evident is the consideration of democratic participation in decisions. The discussion of the dynamic principle is less straightforward. The methodology deals with scenarios of nuclear energy demand up to the end of the century and considers innovative nuclear energy systems that will be deployed in the outlook period. However, a more ample assessment of sustainability is assumed initially. This level of investigation is outside the scope of the methodology. By consequence, the different patterns of nuclear energy deployment are not assessed within this more general view.

The normativity principle and the consideration of subjective aspects are underrepresented. The use of multi-criteria decision-making methodologies and tools is mentioned and warns are given on their use. Subjective (stakeholders) weighting could be used to construct figures of merit in the analysis of environmental stressors.

<table>
<tr><th>INPRO area</th><th>Title</th><th>Dimension of sustainability</th><th>Principles of sustainability</th></tr>
<tr><td>Economic</td><td>-</td><td>Economic/social</td><td>Equity (intra-generational)</td></tr>
<tr><td colspan="4">Energy and related products and services from nuclear energy systems shall be affordable and available.</td></tr>
<tr><td>Infrastructure</td><td></td><td>Institutional</td><td>Equity (intra-generational)</td></tr>
<tr><td colspan="4">Regional and international arrangements shall provide options that enable any country that so wishes to adopt, maintain or enlarge an INS for the supply of energy and related products without making an excessive investment in national infrastructure.[*]</td></tr>
<tr><td>Waste management BP1</td><td>Waste minimization</td><td>Environment</td><td>Integration, equity (intra-generational, intergenerational)</td></tr>
<tr><td colspan="4">Generation of radioactive waste in an INS shall be kept to the minimum practicable.</td></tr>
<tr><td>Waste management BP2</td><td>Protection of human health and the environment</td><td>Environment/social</td><td>Integration, equity (intra-generational, intergenerational)</td></tr>
<tr><td colspan="4">Radioactive waste in an INS shall be managed in such a way as to secure an acceptable level of protection for human health and the environment, regardless of the time or place at which impacts may occur.</td></tr>
<tr><td>Waste management BP3</td><td>Burden on future generations</td><td>Social</td><td>Integration, equity (intergenerational)</td></tr>
<tr><td colspan="4">Radioactive waste in an INS shall be managed in such a way that it will not impose undue burdens on future generations.</td></tr>
<tr><td>Waste management BP4</td><td>Waste minimization</td><td>Environment/social</td><td>Integration, equity (intra-generational, intergenerational)</td></tr>
<tr><td colspan="4">Interactions and relationships among all waste generation and management steps shall be accounted for in the design of the INS, such that overall operational and long-term safety is optimized.</td></tr>
<tr><td>Proliferation resistance</td><td>-</td><td>Social/institutional</td><td>Integration, equity (inter-generational)</td></tr>
<tr><td colspan="4">Proliferation resistance intrinsic features and extrinsic measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that INSs will continue to be an unattractive means to acquire fissile material for a nuclear weapons program. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.</td></tr>
<tr><td>Physical protection</td><td>-</td><td>Social</td><td>Integration</td></tr>
<tr><td colspan="4">Physical Protection Regime shall be effectively and efficiently implemented for the full lifecycle of an INS.</td></tr>
</table>

[*] “Regional and international arrangements shall provide options that enable any country that so wishes” replaced by “Countries shall be able” (IAEA, 2014a).

Table 2.1: Basic principles of the INPRO methodology and sustainable development

<table>
<tr><th>INPRO area</th><th>Title</th><th>Dimension of sustainability</th><th>Principles of sustainability</th></tr>
<tr><td>Environmental BP1</td><td>Acceptability of expected adverse environmental effects</td><td>Environment/social</td><td>Integration, equity (intergenerational)</td></tr>
<tr><td colspan="4">The expected (best estimate) adverse environmental effects of the innovative nuclear energy system shall be well within the performance envelope of current nuclear energy systems delivering similar energy products.</td></tr>
<tr><td>Environmental BP2</td><td>Fitness for Purpose</td><td>Environment/economic/social</td><td>Integration, equity (intergenerational)</td></tr>
<tr><td colspan="4">The INS shall be capable of contributing to the energy needs in the 21st century while making efficient use of nonrenewable resources.</td></tr>
<tr><td>Safety BP1</td><td>defence in depth</td><td>Social</td><td>Integration, equity (intra-generational)</td></tr>
<tr><td colspan="4">Installations of an Innovative Nuclear Energy System shall incorporate enhanced defence-in-depth as a part of their fundamental safety approach and ensure that the levels of protection in defence-in-depth shall be more independent from each other than in existing installations.</td></tr>
<tr><td>Safety BP2</td><td>Inherent safety</td><td>Social</td><td>Integration, equity (intra-generational)</td></tr>
<tr><td colspan="4">Installations of an INS shall excel in safety and reliability by incorporating into their designs, when appropriate, increased emphasis on inherently safe characteristics and passive systems as a part of their fundamental safety approach.</td></tr>
<tr><td>Safety BP3</td><td>risk of radiation</td><td>Social/environment</td><td>Integration, equity (intra-generational)</td></tr>
<tr><td colspan="4">Installations of an INS shall ensure that the risk from radiation exposures to workers, the public and the environment during construction, commissioning, operation, and decommissioning, are comparable to the risk from other industrial facilities used for similar purposes.</td></tr>
<tr><td>Safety BP4</td><td>RD&D</td><td>Institutional/social</td><td>Dynamic</td></tr>
<tr><td colspan="4">The development of INS shall include associated research, development and demonstration work to bring the knowledge of plant characteristics and the capability of analytical methods used for design and safety assessment to at least the same confidence level as for existing plants.</td></tr>
</table>

Table 2.2: Basic principles of the INPRO methodology and sustainable development

General comments are worth on the approach applied in the methodology. The analysis of safety and waste management is strongly based on the studies performed since the beginning of the use of nuclear energy. Physical protection, economic, and proliferation are also disciplines quite traditional in the culture and knowledge of nuclear energy. The infrastructure and environment areas are certainly more innovative and devoted to consider more recent requirements for the future development of nuclear energy. The use of standards and acceptance limits is therefore fairly consistent with the history of nuclear energy.

The scientific community has raised doubts on the compliance of the IAEA’s methodology with the principles underpinning a sustainable development. This analysis has confirmed an under-representation of part of aforementioned principles. The approach is markedly featured by the use of standards and acceptance limits firmly based on the culture and history of nuclear energy. The methodology appears to be on the one hand linked to the past of nuclear energy on the other hand devoted to construct a conceptual framework that could support its development in the future. The interaction of quite different paradigms and the underpinning objective to support its own growth makes difficult to achieve a synthesis with results sometimes less satisfactory.

The methodology presents a partial comparison with alternative technologies and a limited consideration of the dynamic principle. The methodology aims to verify the capability of innovative nuclear systems to supply needed energy in a more ample consideration of sustainability. For the purpose, the definition of the acceptance limits employed in the assessment are internally set without reconsidering the results in the light of a more general consideration of sustainability.

3. DESCRIPTION OF THE METHODOLOGY

3.1 Introduction

The objective of this study is to integrate recent developments on the assessment of sustainability with an approach coherent with the INPRO methodology. For the purpose, a framework for the assessment of nuclear energy sustainability has been constructed; see Fig. 1.1. The methodology consists of different steps that are briefly described.

The initial part of the assessment is focused on the choice of indicators by all stakeholders that should also agree on the alternatives to be considered in the analysis. The determination of indicators needs to acquire proper data and information on each alternative. Quantitative and non-quantitative indicators should be included in the assessment. This initial part is strongly linked to the conditions considered in a specific case study. Involvement of stakeholders and experts through interviews and questionnaires should be mandatory to validate the model. This part requires significant efforts and time. The results presented in following chapters are based on a review of technical and economic specifications. Non-quantitative indicators have been defined through the expert judgment of the author. The choice of stakeholders and criteria has been determined through expert judgments as well. However, the objective of the work should not be undermined by these limitations mainly due to lack of resources and time.

The method used to implement the initial conditions assumed in the study is the Analytic Network Approach (ANP). This method is capable to treat quantitative and non-quantitative criteria and permits to discuss the role assigned to each stakeholder. In addition, the tool applied in presented analyses allows the user to introduce constraints on specific alternative once, for example, stakeholders' requirements suggest an unrealistic expansion. In paragraph 3.2 economic quantities and methods for their determination are presented. This part and the modeling of technologies included in the analysis are prerequisites to the evaluations of all indicators and their relevance. This latter topic is presented in paragraph 3.3, where ANP is presented, and 3.4 where the choices made by the author and the model applied in presented results are discussed.

The priorities of technologies consistent with the stakeholders' viewpoints form the initial indications used for the addition of new electrical capacity in the power sector. Besides other parameters such as growth in electricity demand, curve of loading, planning reserve margin, and dispatch rule, the implementation of alternatives' priorities depicts a power sector evolving in agreement with the indications of stakeholders. As done previously, the author has defined through his judgment parameters whose information was missing. This part is presented in paragraph 3.5 where a description of the LEAP code is also found.

Curves of nuclear energy development are part of the results obtained by means of LEAP. This information is used to calculate quantities specific of the nuclear fuel cycle considered in the study (natural uranium demand, amount of spent fuel, radiotoxicity, etc.).

The indicators adopted for the assessment of nuclear energy sustainability have been identified moving from the GAINS framework. These aspects are discussed in paragraph 3.6. In this paragraph it is found a brief description of the INPRO methodology, the GAINS project, and DESAE.

Values of indicators are then used for the final assessment through the use of ANP as presented in paragraph 3.7.

Overall, the methodology proposed here permits to cope with some relevant issues that the scientific community has judged relevant for the assessment of sustainability: participation of stakeholders, intra-generational equity issues such as the participation of local communities for a fair distribution of burdens and benefit, the consideration of the public opinion. All these factors have been judged to be underrepresented in the INPRO methodology. Intergenerational issues such as radioactive waste and global warming due to GHG are also accounted in the model.

This framework permits to adopt a flexible structure where quantitative and non-quantitative indicators are taken into account improving the consideration of the normative principle. The assessor can assign lower weights to more uncertain information so that a precaution principle could be adopted in the analysis. In comparison with the INPRO methodology a specific consideration is given to the analysis of the power sector. The competition of alternative options and a closer consideration of alternative pathways enhance the consideration of the dynamic principle.

The methodology permits through the use of ANP in its concluding part to adopt a more flexible approach providing indications on what could be preferable rather than a strict dichotomy between sustainable vs. unsustainable. This is also mirrored in the consideration of the acceptance limits that is a relevant aspect of the INPRO methodology and whose application has been dropped in the approach presented here.
It is worth recalling that the acceptance limits used in the INPRO methodology are set internally and not discussed in a more general view of sustainability.

The methodology proposed here aims to be more consistent with the indications of the scientific community that intend the assessment of sustainability as a good opportunity to structure the complexity of a problem, to provide consistent information conveying different viewpoints to the level of decision-making.

3.2 Electricity generation technologies: economic performance

The deployment of a nuclear energy plant is composed of two steps: the offering of a specific technology in a given market by developers; the acquisition of the technology by technology users. At the time a decision is being made, the technology user needs confidence that a given power plant will deliver electricity at a competitive price to earn an adequate return. Nuclear power plants should therefore be capable of appreciable economic performance in comparison with competing technologies. This aspect is fundamental in the analysis of nuclear energy sustainability. Therefore, economic indicators are part of the framework discussed in this study.

In this regard, the maturity of a nuclear technology is a key issue. Mature nuclear power plants have a predictable economic performance thanks to the reduction of the high uncertainties encountered in the evaluation of R&D needs occurring in more innovative systems. It is worth reminding that the development of a nuclear power design requires tens of years. Innovative systems need that governments have a stable and supporting policy so that the more innovative is the system, the longer will be the development phase and the greater will be the uncertainty concerning a successful outcome. The proposed layout has been applied to mature and evolutionary systems. The economic comparison with other technologies is in this case more reliable.

The levelized unit energy cost (LUEC) is a reference parameter when quite different technologies are being compared. The attractiveness of investment has been studied by means of the net present value (NPV) and the return on investment (ROI). Affordability has been discussed in terms of total investment.

A detailed economic analysis requires nearly 150 inputs, however, a simplified approach that employs a smaller number of quantities proved to be fairly consistent with the outcomes of more complex models (IAEA, 2013a; IAEA, 2014b). Calculations have been performed according to the MIT 2003 model available in the version 3 of the Nuclear Economics Support Tool (NEST) (IAEA, 2014b). The economic determinations presented here have been obtained through the model for alternative plants (number 4). This model has been tailored for the use foreseen in the framework. The refinements introduced in the code have been verified against a well-assessed and consistent set of information as discussed in chapter 5. A new description of the LUOM factor has been implemented to account for a price of fuel expressed in terms of electricity produced. The method adopted in the evaluation of the economic parameters is briefly outlined (Ansolobehere et al., 2003, IAEA, 2014b).

Levelized unit energy cost (LUEC)

This quantity represents the price of electricity that permits to cover the expenditures occurring during the lifetime of a given power plant. Notwithstanding some limitations are often highlighted in its definition (e.g., the hypothesis of constant price of electricity), it is generally recognized that this parameter gives useful indications especially dealing with quite different types of technologies (e.g., nuclear, coal-fired power plants). LUEC (mills/kWh) is the sum of two factors: capital costs (LUAC) and the sum of O&M and fuel costs (LUOMF).

$$LUEC = LUAC + LUOMF \tag{1}$$

The definition of LUAC is presented in Eq. (2):

$$LUAC = \frac{ONT}{Lh} \cdot \sum_{t=t_{START}}^{0} \frac{\omega_t \cdot (1+in)^t}{(1+rn)^t} \tag{2}$$

Where *ONT* is the total overnight cost; *Lh* is an intermediate parameter (hours); ω_t is the normalized distribution of funds over the construction period from t_{START} to 0 (negative values); *in* (%/100) is the annual inflation rate. ω_t and *in* are inputs, *rn*, expressed in %/100, is a nominal discount rate which is defined as follows:

$$rn = dir \cdot df + eir \cdot (1 - df) \tag{3}$$

where *dir* (%/100) is the debt interest rate, *eir* (%/100) is the equity interest rate and *df* (%/100) is the debt fraction. The nominal discount rate (*rn*) becomes a real discount rate (*r*) if inflation is equal to zero (*in* = 0). The equation (3) permits to consider shares of investment (equity and debt) but not different payback periods for equity and debt.

LUOMF is calculated according to the correlation:

$$LUOMF = \frac{1}{Lh} \cdot \sum_{1}^{t_{END}} (Cfe_t + Cw_t + Comf_t + Comv_t + Cdec_t + Cinc_t) \tag{4}$$

In calculations, the correlation (4) has been modified by introducing the net electrical output to be dimensionally consistent with the LUAC factor.

The discounted cost of fuel, nuclear or fossil, per year of operation Cfe_t (USD/yr) includes inflation and escalation rates:

$$Cfe_t = \frac{8760 \cdot Lf \cdot P \cdot Cfkg \cdot (1 + rfe)^t \cdot (1 + in)^t}{Q \cdot \eta \cdot (1 + rn)^t} \tag{5}$$

where *rfe* (%/100) is the real annual fuel cost escalation rate, Cfkg (USD/kg_{HM}) is the average cost of nuclear fuel per kg of heavy metal. In calculations, the cost of fuel has been expressed in (USD/MWh). The introduction of this change has permitted to apply the same economic model to all the technology considered in the analysis.

The discounted cost required to treat the high level waste produced per year of power plant operation Cw_t (USD/yr) includes the inflation rate and is defined in Eq. (6).

$$Cw_t = \frac{8760 \cdot Lf \cdot P \cdot W \cdot (1 + in)^t}{(1 + rn)^t} \tag{6}$$

where W (mills/kWh) is the waste fee. In this study, the cost of nuclear fuel accounts for the expenditures occurring both in the front-end and back-end of a given fuel cycle.

The discounted fixed part of the yearly O&M cost (USD/kWe) $Comf_t$ (USD/yr) is calculated by means of Eq. (7):

$$Comf_t = P \cdot (O\&M)_{FIX} \cdot \frac{(1+rom)^t \cdot (1+in)^t}{(1+rn)^t} \tag{7}$$

Where rom (%/100) is the real O&M cost escalation rate.

The discounted variable part of the yearly O&M cost (USD/kWh) is taken into account through the factor $Comv_t$ (USD/yr) that includes inflation and escalation:

$$Comv_t = 8760 \cdot Lf \cdot P \cdot (O\&M)_{VAR} \cdot \frac{(1+rom)^t \cdot (1+in)^t}{(1+rn)^t} \tag{8}$$

The discounted annual fee for the decommissioning of electricity generating plants $Cdec_t$ (USD/yr) is based on the total cost D and the nominal discount rate in agreement with the correlation given in Eq. (9):

$$Cdec_t = \frac{D}{t_{END} \cdot (1+rn)^t} \tag{9}$$

The decommissioning cost of nuclear energy has been assumed to be 15% of the total overnight cost. This quantity has been reduced to 5% in the case of non-nuclear electricity generating plants.

The incremental capital cost per year of operation $Cinc_t$ (USD/yr) inflated and discounted is defined in Eq. (10):

$$Cinc_t = ICC \cdot P \cdot \frac{(1+in)^t}{(1+rn)^t} \tag{10}$$

where ICC (USD/kW(e) / yr) is a specific incremental capital cost per year of operation. It has been assumed that no incremental capital costs are considered.

Net present value (NPV)

The net present value (NPV) is expressed in USD/kWe. This quantity indicates the net benefit of a given project. It gives an evaluation of the discounted incomes and expenses occurring in the course of the plant lifetime. The price of electricity is an input of the model.

$$LNPV = (PUES - LUEC) \cdot Lf \cdot 8760 \cdot \frac{1 - \left(\frac{1}{1+rn}\right)^{Plantlife+1}}{1 - \left(\frac{1}{1+rn}\right)} \tag{11}$$

In Eq. (11), PUES is the price of electricity expressed in mills/kWh, *Plantlife* is the duration of the electricity generating plant expressed in years.

Return on investment (ROI)

The return on investment (ROI) is an indicator of the mean net annual income, i.e. the total income resulting from the sale of electricity produced by the plant less the O&M and fuel costs and other costs (i.e., waste management, decommissioning) occurring over the plant lifetime.

ROI is the ratio of the net annual income over the total overnight cost. It is not a discounted or levelized quantity so that it is not depending on the real discount rate. The higher the ROI the more attractive is the investment. This parameter has been calculated by means of Eq. (12) that has been introduced for the purpose in the NEST code.

$$ROI = \left(\frac{(PUES - FUEL - O\&M_{VAR}) \cdot 8760 \cdot Lf - 1000 \cdot O\&M_{FIX} - D/P}{ONT \cdot 1000} \right) \tag{12}$$

In this correlation, *D* is the yearly amount for decommissioning costs and *P* is the electrical capacity of the power plant. Remaining factors are consistent with previous descriptions.

The determination of the economic indicators has been based on a review of the technical and economic specifications of the technologies included in the analysis. Two values of discount rate have been assumed (5%, 10%). These values are usually considered suitable to cover the range encountered by both institutional and private investors. Inflation, tax rate, and escalation factors have not been discussed. The distribution of the expenditures occurring in the course of the construction phase of a power plant has been assumed constant.

3.3 Participation of stakeholders and determination of technologies' priorities

The inherent multidimensional essence of sustainability requires the definition of a set of indicators that could properly represents the complexity of the topic under consideration. This in turn brings the need to apply specific methods and tools where a traditional optimization approach is not suitable for the purpose. This latter approach is certainly helpful when a single criterion is taken into account in the process of decision-making. Different MCDM methods are available and have been applied in studies on the energy sector.

A review of these methods can be found in (Løken, 2007). The author groups available methods in three main categories; value measurement models; goal, aspiration and reference level models; outranking models. The first method assigns a value to each alternative so that preferences are evidenced in comparing two alternatives, moreover, weights are linked to each criterion so that for each alternative it is possible to calculate an overall ranking (Multi Attribute Value Theory, MAVT). The Analytic Hierarchy Process (AHP) is somehow close to the Multi Attribute Utility Theory (an extension of MAVT) (Saaty, 1980). The method applied in the methodology proposed here is a generalization of AHP and is named Analytic Network Process (ANP) (Saaty, 2001). A distinctive characteristic of AHP is the use of pairwise comparisons that are employed both to compare alternatives with respect to each criterion and to estimate criteria weights. Pairwise comparisons are carried out according to a specific scale.

In the goal modeling it is attempted to find a feasible solution that minimizes the vector of deviational variables. TOPSIS is a method that could be classified in this latter group. In the outranking models, alternatives are pairwise compared to check which of them is preferred with regard to each criterion. When aggregating the preference information for all relevant criteria, the model determines at what extent one of the alternatives can be said to outrank another. Methods such as ELECTRE and PROMETHEE are included in this category so that it is often reported that outranking methods refer to the so-called French school.

The extensive review of MCDM methods presented in (Wang, 2009) highlights a widespread application of AHP. In their conclusions authors state that the use of an aggregation of different methods is more rationale in sustainability assessments. In the frame of the bioenergy sector, a review of MCDM methods is also presented in (Scott et al., 2012).

The determination of technologies' priorities in agreement with stakeholders' viewpoints is carried out by means of ANP (Saaty, 2001). Stakeholders should define criteria and their weights. Outcomes of this step should be assumed as the initial indications for the development of energy policies agreed among stakeholders.

An ANP model is a network of nodes and links among them representing the spread of influence or dominance of each node across the entire network. A node can be an alternative (e.g., a specific electricity generating system) or a criterion. Each node can be influenced by all the nodes in the network permitting the existence of feedbacks. These relationships represent a concept of dependence or dominance that should be maintained during the development of the model. Pairwise comparisons with respect to each source of dominance are carried out according to the scale presented in Tab. 3.1. The principal eigenvector of these judgments (local priorities) is then introduced in the supermatrix. This matrix contains the principal eigenvectors representing all the relationships existing in the network. Judgments given through pairwise comparisons should be consistent. This prerequisite is assured for values of the consistency ratio (CR) below 10%.

This initial supermatrix is named unweighted supermatrix. Set of homogeneous criteria are included in so-called clusters and weights can be assigned to each cluster by means of pairwise comparisons. This information is contained in the cluster matrix that is used to multiply the corresponding elements in the unweighted matrix. The resulting supermatrix is called weighted supermatrix. Finally, the weighted supermatrix is raised to the power. Iterations are concluded when the elements of the supermatrix do not change significantly in comparison with previous step. Elements of the final supermatrix are the priorities of alternatives and criteria. These steps are figured out in Fig. 3.1.

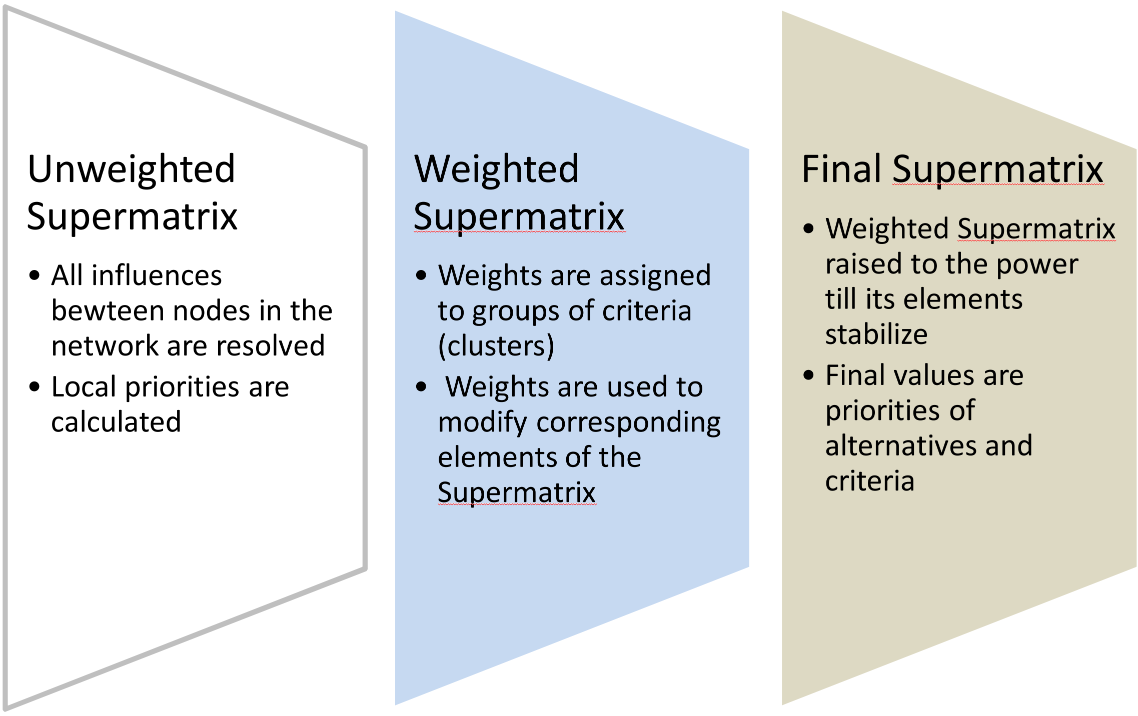
Judgment	**Value**
Equal importance	1
Moderate importance of one over the other	3
Strong or essential importance	5
Very strong importance or demonstrated importance	7
Extreme importance	9
Intermediate values	2, 4, 6, 8

Table 3.1: Scale of pairwise comparisons (AHP/ANP)

A review of recent ANP applications in the energy sector is given. A two-layer ANP model to study the choice of fuel for residential use in Turkey is presented in (Erdoğmuş et al., 2006). The article underlines the role that stakeholders should play in the determination of criteria and decision models. Önüt et al. (2008) present a review of the energy resources required in the Turkish industry and show a comparison of their performance according to a multiple criteria decision-making approach (ANP). In particular, the authors employ a four-layer network with a BOCR (Benefits-Opportunities-Costs-Risks) structure at the bottom.

Yi et al. (2011) discuss which renewable energy could be used in North Korea to overcome its energy shortage. Authors apply a two-layer AHP approach and employ panels of experts to define clusters' weights and pairwise comparisons of the alternatives. For the purpose, two surveys have been performed in two different stages of research. In conclusions, the authors point out that their research was not able to provide a concluding answer due to the disagreement seen in the opinions of the overall panel and sub-panels of experts that did not match the final priorities provided by the analytic tool.

A fuzzy analytic network process has been used by Lee et al. (2012) to help in selecting a wind turbine. Liang et al. (2013) employ ANP to determine the most sustainable option to recover waste energy from engines. Authors compare the outcomes of AHP and ANP and propose an alternative approach to express the interdependencies existing among criteria. This method avoids the use of the supermatrix concept (Liang et al., 2013). Authors highlight the relevant role of experts' interviews for the definition of the weights applied in calculations.



Unweighted Supermatrix

- All influences bewteen nodes in the network are resolved
- Local priorities are calculated

Weighted Supermatrix

- Weights are assigned to groups of criteria (clusters)
- Weights are used to modify corresponding elements of the Supermatrix

Final Supermatrix

- Weighted Supermatrix raised to the power till its elements stabilize
- Final values are priorities of alternatives and criteria

Figure 3.1: ANP procedure (Saaty, 2001)

Kabak and Dağdeviren (2014) propose a hybrid approach to the problem of prioritizing renewable energy sources. Authors have developed ANP models based on BOCR layers and a set of strategic criteria whose weights have been determined in agreement with a team of experts. In particular, each cluster of the BOCR model has been compared by experts with respect to each strategic criterion through the use of an agreed linguistic scale (Kabak and Dağdeviren, 2014).

Atmaca and Burak Basar (2012) present an analysis of the alternatives considered for the future energy policy of Turkey. According to the outcomes of ANP, nuclear energy should have the highest priority. ANP has been also applied to select the site where to convey and treat the municipal solid waste of Valencia (Aragonés-Beltrán et al., 2010). Siting issues are also discussed in (Tuzkaya et al., 2008). In this article, the authors present a comprehensive illustration of the ANP methodology and an application based on a two-layer schema.

Cannemi et al. (2014) discuss the investors' attitudes towards different projects of biomass plant. The study confirms the ANP capabilities to improve policies and to help in achieving the targets fixed by the national Parliament. The author has previously published two studies where ANP is applied to the power sector especially to investigate the sustainability of nuclear energy (Calabrese, 2013c, Calabrese, 2016).

ANP has been widely applied to study different aspects of the energy sector and confirmed to possess all the capabilities required for the purpose; see Fig. 3.2. Methods usually employed to validate the initial conditions adopted in a MCDM analysis have not been used here due to the limitation of resources and time. This fact has suggested limiting the number of initial hypotheses as a general rule in the development of the ANP model.

The implementation of the ANP model and the determination of the technologies' priorities have been carried out by means of Super Decisions (Super Decisions, 2016). This tool is freeware and offers all the resources necessary for the analysis of single layer, two-layer or more complex networks of elements.

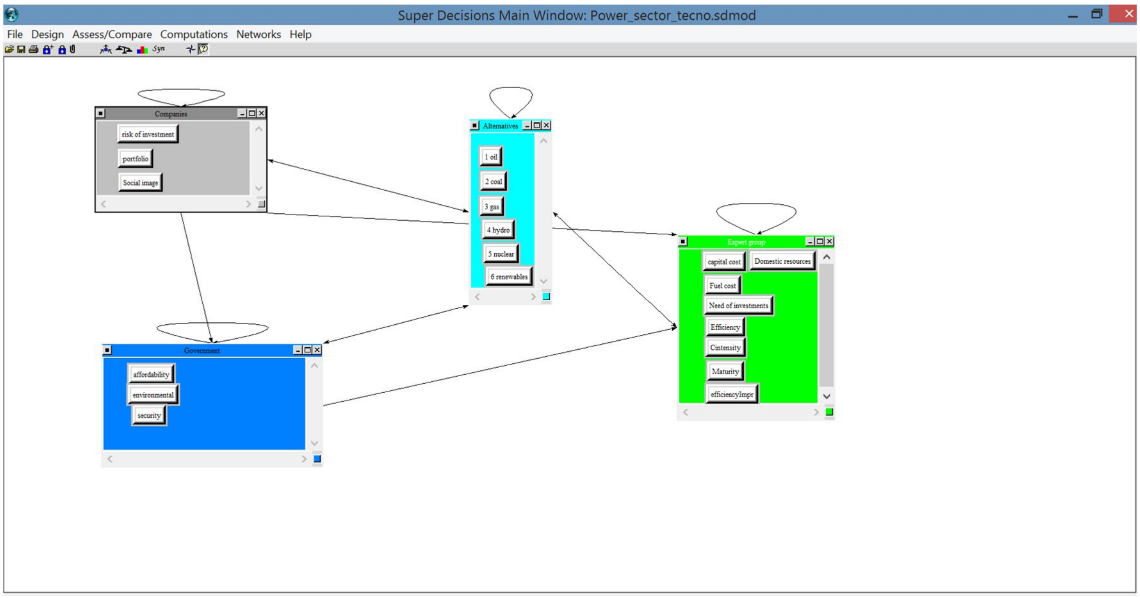


Figure 3.2: Single-layer model: clusters, alternatives, criteria and their relationships as presented in the Super Decisions editor

3.4 Model for the definition of policies in the power sector

Modeling has been carried out by means of a single-layer network. As aforementioned, it has been decided to reduce the number of criteria per cluster to avoid that the numerical burden could lead to misleading interpretations of the relationships existing among elements. Feedbacks from alternatives to criteria and inner dependencies have been avoided as well. These choices besides a limitation in the burden of numerical load aim to reduce the hypotheses and assumptions underpinning resulting priorities. Pairwise comparisons have been carried out by the author (expert judgment). As aforementioned, interviews or surveys of individuals that could properly represent the stakeholders' viewpoints are recommended in the literature to validate models and their outcomes. Therefore, this initial step should be tailored for the assessment under consideration.

The stakeholders included in the model proposed here are: government, private firms, public opinion. According to this initial assumption, modeling is composed of six clusters presented in Fig. 3.3.

In the *Alternatives* cluster six technologies for electricity generation are considered:

- nuclear;
- coal;
- natural gas;
- hydro;
- onshore wind;
- solar PV.

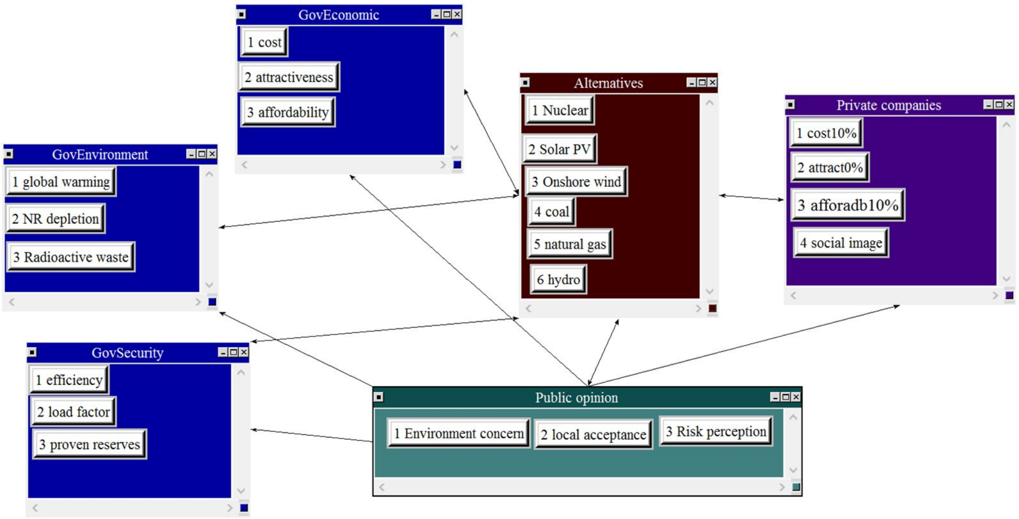


Figure 3.3: ANP model for the definition of technologies' priorities

The *Private companies* cluster contains following criteria: cost, attractiveness, affordability, social image. The definition of criteria employed by private companies/investors is mostly based on the assumption that most significant drivers of their strategies are a compromise between risk of investment and attractiveness of investment. However, the social image is also a significant factor for their business plans. Several parameters may affect the price of electricity and expected revenues. The risk of investment in fuel-intensive technologies is usually paid by consumers, differently in the case of capital-intensive technologies. The economic parameters of this cluster have been determined by assuming a discount rate of 10%. Their numerical values have been calculated by means of NEST as presented in previous paragraphs.

The key role of governments in determining the energy policy of a country is generally acknowledged. Governments should purse economic, environment, and security of supplies objectives. Accordingly, three clusters stand for these important government's targets.

The economic cluster contains the same criteria used by private companies. The discount rate is 5%. Environment objectives are mostly focused on three issues: global warming, depletion of non-renewable natural resources, radioactive waste. Finally, the security of energy supplies is figured out by following criteria: efficiency, load factor, proven resources.

The public opinion is represented as generally worried about environment, and somehow featured by a NIMBY attitude (Not In My Back Yard). Risk perception is also part of its attitude towards electricity generating alternatives.

Overall the model is composed of 6 clusters and 16 indicators. Modeling is composed of opposing criteria as well as quantitative and non-quantitative criteria that are both peculiar aspects of MCDM analyses. Notwithstanding they have been grouped by stakeholder, criteria could be also be classified according to the typical dimensions of sustainability assessment: economic, environmental, and social.

Some more details are needed about the criteria included in the public opinion cluster. Environment concern is intended as a general feeling that is mostly influenced by the messages conveyed by media on the urgency of risks such as global warming or water shortage. Risk perception is mostly an individual attitude due to personal beliefs, experiences, and values. Perceived risk is usually higher than the estimations provided by scientific approaches. Risks of severe or catastrophic accidents are fundamental in shaping the public attitude towards nuclear. The local acceptance criterion has been assumed to be mainly shaped by the electrical capacity of each plant. Distributed generation is usually better accepted by local communities involved in the construction of new power plants.

As aforementioned, the model does not contain inner dependencies (self-loop) while outer dependencies from the public opinion cluster have been introduced. Links are directed towards the government clusters and the private company cluster to account for the role played by the public in the definition of energy policies.

The outer dependencies introduced in the model are:

- environment concern affects all criteria in government environment, government security, and private companies;
- local acceptance affects all criteria in government environment, private companies;
- risk perception affects government economic, government security, private companies.

Local priorities have been introduced by means of pairwise comparisons by assuring that the consistency ratio is below 10%. Local priorities are therefore based on expert judgments and should be properly validated. Numerical criteria have been introduced directly and their compliance with the ANP scale and requirements on the consistency ratio verified.

Tab. 3.2 resumes the local priorities of criteria included in the model. Each row presents the normalized priorities by criterion. This information has been extracted from the unweighted supermatrix. These indications are obtained by means of pairwise comparisons in which two alternatives are compared with respect to a certain criterion provided that the compliance with the scale presented in Tab. 3.1 and the consistency of judgments are assured. Once all pairwise comparisons have been determined, the code calculates the principal eigenvector that resumes all judgments given with respect to each criterion. The data reported in Tab. 3.2 corresponds to the principal eigenvectors of corresponding criteria.

	Nuclear	**Solar PV**	**Onshore wind**	**Coal**	**Natural gas**	**Hydro**
cost	0.16804	0.0926	0.21755	0.1878	0.1298	0.20421
attractiveness	0.3261	9.00E-05	0.09823	0.24395	0.14269	0.18893
affordability	0.00556	0.3115	0.45718	0.05008	0.13225	0.04344
global warm.	0.23116	0.23116	0.23116	0.02513	0.05025	0.23116
NR depletion	0.01254	0.31344	0.31344	0.03297	0.01416	0.31344
radioactive waste	0.00243	0.24331	0.24331	0.02433	0.24331	0.24331
efficiency	0.08845	0.2457	0.2457	0.09091	0.10811	0.22113
load factor	0.22368	0.03947	0.06579	0.22368	0.22368	0.22368
proven reserves	0.01254	0.31344	0.31344	0.03297	0.01416	0.31344
cost 10%	0.13359	0.09129	0.21768	0.21094	0.17673	0.16977
attractiveness 10%	2.40E-04	0.00102	0.16839	0.39841	0.34246	0.08948
affordability 10%	0.00502	0.31544	0.46297	0.04709	0.12758	0.0419
social image	0.03299	0.31612	0.31612	0.07384	0.13046	0.13046
environ. concern	0.02409	0.3743	0.27198	0.04758	0.09855	0.18351
local acceptance	0.02394	0.383	0.383	0.06383	0.06964	0.0766

Table 3.2: Local priorities of by criterion (extracted from the nweighted supermatrix)

Tab. 3.3 presents the local priorities describing the outer dependencies from the public opinion cluster towards the other clusters included in the model. Priorities are normalized by cluster and what has been said in the case of Tab. 3.2 holds for this table too.

The principal eigenvectors showed in these tables have been obtained through expert judgments and should be properly validated as a mandatory step for the robustness of the assessment. These indications have been used for testing purpose and do not represent real viewpoints.

Some parts of the supermatrix are null because it has been decided to avoid large numbers of inner and outer dependencies based on additional hypotheses that could not be justified within the scope of the study.

Another important aspect for the determination of priorities is the weight assigned to each cluster that in this case represents the actual importance/role of each stakeholder in the decision-making process.

Cluster	**Criteria**	**environment concern**	**local acceptance**	**risk perception**
Government Economic	**cost**	0.00000	0.20000	0.20000
	attractiveness	0.00000	0.20000	0.60000
	affordability	0.00000	0.60000	0.20000
Government Environment	**global warming**	0.45996	0.00000	0.20000
	NR depletion	0.31892	0.00000	0.20000
	radioactive waste	0.22112	0.00000	0.60000
Government Security	**efficiency**	0.54995	0.00000	0.00000
	load factor	0.24021	0.00000	0.00000
	proven reserves	0.20984	0.00000	0.00000
Private Companies	**cost 10%**	0.16667	0.10000	0.12500
	attractiveness t0%	0.16667	0.10000	0.37500
	affordability 10%	0.16667	0.40000	0.12500
	social image	0.50000	0.40000	0.37500

Table 3.3: Outer dependencies from the Public Opinion cluster (extracted from the nweighted supermatrix)

3.5 Analysis of the power sector

As mentioned in the introduction, a sustainability assessment should comply with the dynamic principle where alternative patterns of change are properly taken into account. Therefore, the assessment of nuclear energy should properly account for the performance of alternative systems. Beside this aspect, other factors are also worth to be properly considered in an assessment. Dispatch rule, load curve, and planning reserve margin are all relevant quantities for evaluating the performance of electricity generating systems. The addition of renewables to meet base load certainly affects nuclear power plants. It is therefore important that the policies agreed by stakeholders are carefully discussed in the light of a real power sector. Moreover, primary resources requirement, unmet demand, and environmental loading should be part of an assessment of sustainability that is based on an ample consideration of the aspects involved in the problem.

It is worth reminding that the evolution of the power sector should be coherent with the indications of the stakeholders that are resumed in the priority assigned to each technology. However, the existing power mix has a relevant impact on the future of this sector. New policies may be effective only when retirements or increasing demand give the opportunity to modify existing conditions. Technology lock-in may introduce a significant delay in the transition to a new agreed energy mix.

The analysis of the power sector is carried out by means of LEAP (Long range Energy Alternatives Planning System). This code has been developed at the Stockholm Environment Institute (Heaps, 2012). LEAP has been employed by thousands of organizations in more than 190 countries worldwide. Among its users there are governmental agencies, academics, non-governmental organizations, consulting companies, and energy utilities (LEAP, 2016). LEAP has become widely used in countries willing to undertake integrated resources planning, greenhouse gas mitigation assessments, and low emission development strategies.

The LEAP methodology is based on building the energy use and supply database and extending it further to simulate various scenarios of energy demand and supply. LEAP can be used as an energy accounting tool to study subjects such as: physical description of energy systems, GHG abatement potential, costs associated with energy systems, other environmental impacts.

The code tracks consumption and production of energy and the need for resources in all sectors of an economic system. It can be used to account for both the energy sector and non-energy sector greenhouse gas emission sources and sinks. In addition to tracking GHG, LEAP can also be used to analyze the emissions of local and regional air pollutants, making it well-suited to studies about the climate co-benefits of local air pollution reduction.

LEAP is a tool designed to analyze medium- and long-range scenarios (10-50 years) of different storylines of the energy sector. The code has the capabilities to compare alternative energy policies. In view of the use in this study, LEAP provides accounting and simulating resources suitable for the analysis of a typical transformation sector such as the power sector.
The LEAP model has a built-in database called the Technology and Environmental Database (TED) that contains the emission factors of different fuels and transformation technologies. TED includes data on hundreds of technologies, referencing reports by dozens of institutions including the Intergovernmental Panel on Climate Change (IPCC), the U.S. Department of Energy, and the International Energy Agency.

Several applications are available on the website (LEAP, 2016). Some articles that present applications of the LEAP code are briefly resumed.

Kim et al. (2011) employ the LEAP code for evaluations on the energy future of the Republic of Korea. The authors discuss several policy-based scenarios up to 2030 featured by different levels of nuclear energy deployment. Huang et al. (2011) study different patterns of development in Taiwan. The focus of the article is on the power sector. Wang et al. (2011) analyze the difficulties faced by China to maintain its economic growth while reducing pollutant emissions. Authors present main achievements and impacts of several energy policies.

Takase and Suzuki (2011) describe the Japanese energy sector accounting for energy demand, supply by fuel and by sector. Authors focus on policies devoted to meet climate change targets, renewable energy development and deployment, liberalization of energy markets, and evolution of the Japanese nuclear power sector. The investigation has been based on a specific dataset of Japan consistent with the structure of LEAP (Takase and Suzuki, 2011).

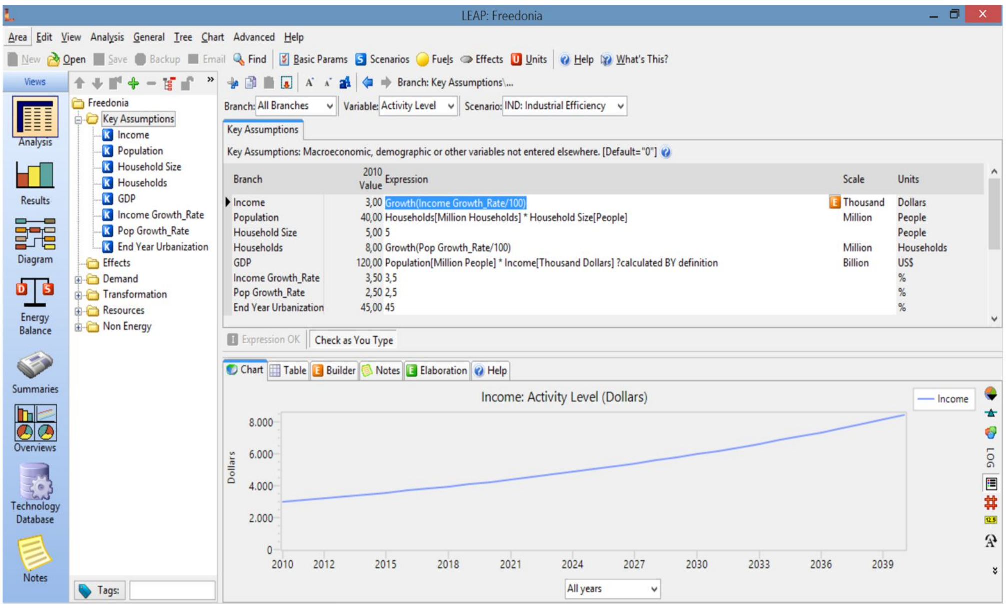
The LEAP code has been employed in the SEPIA methodology (Sustainable Energy Policy Integrated Assessment) for the development of a sustainable energy policy especially in regard to the involvement of stakeholders (Laes et al., 2011b). SEPIA combines participatory fuzzy-set multi-criteria analysis with narrative scenarios building while the quantitative modeling of energy systems is performed by using LEAP models (Laes et al., 2011b).

Subramanyam et al. (2015) develop Sankey diagrams mapping the energy flow for both demand and supply sides of the Alberta province (Canada). For this purpose, the authors have implemented a LEAP model.

The LEAP code has been employed in this study for the analysis the power sector to consider environmental impacts, especially the global warming potential of proposed scenarios, primary energy requirements and depletion of non-renewable resources. Production costs have been considered as well. These latter costs to society (sometimes called opportunity costs) do not coincide with the price paid by final customer. The evaluation of the 100-year Global Warming Potential (GWP) accounts for CO_2, N_2O, and CH_4 emissions (IPCC, 2013).

The analyses presented here are based on the technical and economic specifications presented in chapter 4. Parameters such as load curve, planning reserve margin, and dispatch rule should be properly defined. Economic conditions (e.g., discount rate) should be provided as well.

The bridge linking previous step (ANP model) with this step (LEAP model) is represented by the priorities of electricity generating technologies. The LEAP code makes a distinction between exogenous and endogenous electrical capacity. While the former is defined by the user, the latter is added by the code according to the peak of demand and the adopted planning reserve margin. The exogenous capacity may well represent existing plants and their retirement curves. The endogenous capacity implements a new energy policy indicating which types of plant should be preferably introduced in the model to substitute retirements and to meet demand. Size and order of addition may be defined by the user, time and amount of additional capacity is left to the code. Order and ratio of addition of each technology are determined by means of the MCDM model and properly introduced in LEAP.



Branch: All Branches Variable: Activity Level Scenario: IND: Industrial Efficiency

Key Assumptions: Macroeconomic, demographic or other variables not entered elsewhere. [Default="0"]

Branch	2010 Value	Expression	Scale	Units
Income	3,00	Growth(Income Growth_Rate/100)	Thousand	Dollars
Population	40,00	Households[Million Households] * Household Size[People]	Million	People
Household Size	5,00	5		People
Households	8,00	Growth(Pop Growth_Rate/100)	Million	Households
GDP	120,00	Population[Million People] * Income[Thousand Dollars] ?calculated BY definition	Billion	US$
Income Growth_Rate	3,50	3,5		%
Pop Growth_Rate	2,50	2,5		%
End Year Urbanization	45,00	45		%

Figure 3.4: Analysis editor of LEAP

3.6 From the GAINS framework to the set of criteria used in the assessment

Through the steps discussed in previous sections the role of nuclear energy is determined in each scenario or energy policy agreed by stakeholders. The objective of research is to integrate the approach used by the IAEA for the assessment of nuclear energy sustainability with more recent developments published by the scientific community in this field. The definition of a specific set of indicators for the purpose has been based on the outcomes of the GAINS project. The outcome of interest is the so-called GAINS framework a tool consistent with the INPRO methodology. A brief introduction of the INPRO methodology and the GAINS framework is therefore necessary.

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is part of the International Atomic Energy Agency (IAEA) (INPRO, 2016). In 2001, INPRO was initiated on the basis of a resolution of the IAEA's 44th General Conference in 2000. INPRO covers a broad range of missions and activities. One of the objectives of INPRO is the investigation and formulation of visions for opportunities and challenges of nuclear energy in the 21st century.
\
Currently, 40 IAEA's Member States are also members of INPRO: Algeria, Argentina, Armenia, Bangladesh, Belarus, Belgium, Brazil, Bulgaria, Canada, Chile, China, Czech Republic, Egypt, France, Germany, India, Indonesia, Israel, Italy, Japan, Jordan, Kazakhstan, Kenya, Republic of Korea, Malaysia, Morocco, Netherlands, Pakistan, Poland, Romania, Russian Federation, Slovakia, South Africa, Spain, Switzerland, Thailand, Turkey, Ukraine, United States of America, and Vietnam. The European Commission (EC) takes part in the INPRO's activities as well.

The objectives of the INPRO methodology have been aligned with the concept of sustainability that, according to the indications of the United Nations (UN), should be considered in its four dimensions: economic, environment, social, and institutional (IAEA, 2008a). The INPRO methodology has been developed especially to determine the sustainability of innovative nuclear energy systems (INS). In INPRO, the concept of INS refers to evolutionary and innovative nuclear systems that will be deployed in the 21st century.

INPRO methodology

The INPRO methodology for an INS is composed of three main parts: screening of nuclear systems consistent with the objective of sustainability, comparison of different architectures and definition of an optimized INS (IAEA, 2008a).

The interest of methodology is focused on a single component as well as the entire system that should be globally sustainable. Therefore, the INPRO methodology requires a comprehensive and holistic assessment. For this purpose, INPRO has established a set of requirements organized in a hierarchy of basic principles, users' requirements, and criteria in seven areas: economics, infrastructure, waste management, proliferation resistance, physical protection, safety, and environment.

A Basic Principle is a general goal that an INS must achieve. It should be a guidance for its development.

A User's Requirement defines how to achieve the objective pursed through a basic principle. For each basic principle, a sustainable INS shall fulfill all users' requirements. In INPRO, a user is an entity that has a stake or interest in potential applications of nuclear technologies.

A Criterion is required to enable an assessor to determine whether and how well a given user's requirement is being met by a given INS. An INPRO criterion consists of an Indicator and an Acceptance Limit. Indicators are based either on a single parameter or an aggregate variable, or on a status statement. This general schema is employed in the analysis of each area of the assessment.

If the outcome of the methodology is not positive, the role of nuclear energy should be adjusted. This result is important in the case that the assessor is a technology user. If the analysis points out the existence of technology gaps, the methodology provides proper indications on the need for RD&D in specific areas. These indications are useful for technology developers.

The GAINS project

The GAINS framework has been conceived within the INPRO Collaborative Project GAINS (Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle) (IAEA, 2013b; Kuznetsov et al., 2013). According to the GAINS framework a limited but still representative number of key indicators could be adopted and suitable for the assessment of nuclear energy sustainability. The GAINS Framework maintains the consistency with the INPRO methodology.

Figure 3.5: INPRO methodology: areas and sustainability assessment approach

The GAINS project has continued the analysis undertaken in the so-called Joint Study regarding the application of the INPRO methodology to a closed nuclear fuel cycle (IAEA, 2010; IAEA, 2013b). The Joint Study was focused on the examination of fast reactors and related fuel cycle technologies in equilibrium with thermal reactors. This study, on the one hand highlighted that the role of innovative nuclear energy systems is fundamental for improving the sustainability of nuclear power, on the other hand confirmed that thermal reactors operating in an open fuel cycle will continue to be the main contributors to the production of nuclear energy at least for several more decades.

The investigations carried out in GAINS have been devoted to the assessment of sustainability of nuclear energy systems entailing several types of technology both existing and innovative that should play a significant role in the 21st century.

The GAINS scenarios have been based on two distinct storylines of nuclear energy development. The first storyline describes a convergent (homogeneous) world with rapid changes towards global solutions of economic, social and environmental challenges. These assumptions create favorable conditions for the unification of reactor fleet, sharing of infrastructures, arrangement of multinational fuel cycle centres, and innovative approaches to financing and licensing. The second storyline depicts a heterogeneous world based on self-reliance and preservation of local identities. Nuclear services across regions converge very slowly, regional differences in availability of material resources, energy growth rate and nuclear energy deployment remain significant.

The GAINS Framework is reported in Tab. 3.4. The distinctive INPRO area of each key indicator (KI) is identified by a bold “X”. The color-coding gives an estimation of relative uncertainties affecting each quantity (IAEA, 2013b; Kuznetsov et al., 2013).

The GAINS Framework has been reviewed under the hypothesis that the time horizon of interest is 2050. In this timeframe mature and evolutionary nuclear power plants are deployed. It is worth recalling that the outlook period of the GAINS scenarios extends up to the end of the century. Results of this review are resumed in Tab. 3.5. Some indicators of the GAINS framework have not been included in our set of indicators because of different reasons: maturity of the technologies considered in the analysis, scope of the study, type of nuclear fuel cycle.

The GAINS project was mainly focused on innovative systems where uncertainties in R&D costs are relevant. Economic evaluations have not been carried out in GAINS. The scope of our assessment has permitted to analyze and extend the number of indicators used to assess this dimension of sustainability.

	Key Indicators and Evaluation Parameters		INPRO assessment areas					
	Color coding indicative of relative uncertainty level in estimating specific quantitative values for future NES (can vary based on a particular scenario)	Low	Resource Sustainability	Waste Management and Environmental Stressors	Safety	Proliferation Resistance and Physical Protection	Economics	Infrastructure
		Medium-low						
		Medium-high						
		High						
Power Production								
KI-1	Nuclear power production capacity by reactor type							**X**
EP-1.1	(a) Commissioning and (b) decommissioning rates			X				X
Nuclear Material Resources								
KI-2	Average net energy produced per unit mass of natural uranium		**X**	X				
EP-2.1	Cumulative demand of natural nuclear materials, i.e. (a) natural uranium and (b) thorium		X	X				
KI-3	Direct use material inventories per unit energy generated (Cumulative absolute quantities can be shown as EP-3.1)		X			**X**		X
Discharged Fuel								
KI-4	Discharged fuel inventories per unit energy generated (Cumulative absolute quantities can be shown as EP-4.1)			**X**				**X**
Radioactive Waste and Minor Actinides								
KI-5	Radioactive waste inventories per unit energy generated[1] (Cumulative absolute quantities can be shown as EP-5.3)			**X**				X
EP-5.1	(a) radiotoxicity and (b) decay heat of waste, including discharged fuel destined for disposal			X				X
EP-5.2	Minor actinide inventories per unit energy generated			X				X
Fuel Cycle Services								
KI-6	(a) Uranium enrichment and (b) fuel reprocessing capacities, both normalized per unit of nuclear power production capacity					**X**		**X**
KI-7	Annual quantities of fuel and waste material transported between groups			X		X		**X**
EP-7.1	Category of nuclear material transported between groups					**X**		
System Safety								
KI-8	Annual collective risk per unit energy generation				**X**			
Costs and Investment								
KI-9	Levelized unit of electricity cost (LUEC)						**X**	
EP-9.1	Overnight cost for Nth-of-a-kind (NOAK) reactor unit: (a) total and (b) specific (per unit capacity)						X	
KI-10	Estimated R&D investment to NOAK deployment						**X**	X
EP-10.1	Additional functions or benefits[2]						X	

Table 3.4: GAINS Framework (IAEA, 2013b)

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[1] Excludes discharged fuel covered by KI-4.

[2] In addition to electrical power production, e.g. high temperature process heat production or transmutation.

Indicator	Description	If applied or reasons for its exclusion
KI-1	Nuclear power production capacity by reactor type	inherited
KI-2	Average net energy produced per unit mass of natural uranium	inherited
KI-3	Direct use material inventories per unit energy generated	once-through fuel cycle
KI-4	Discharged fuel inventories per unit energy generated	inherited
KI-5	Radioactive waste inventories per unit energy generated	inherited
KI-6	Uranium enrichment and fuel reprocessing capacities per unit of nuclear power production capacity	inherited
KI-7	Annual quantities of fuel and waste material transported between groups	global analysis
KI-8	Annual collective risk per unit energy generation	applied (not used in GAINS)
KI-9	Levelized unit of electricity cost (LUEC)	applied (not used in GAINS)
KI-10	Estimated R&D investment to NOAK deployment	mature and evolutionary systems

Table 3.5: Review performed on the indicators of the GAINS framework

Table 3.6 presents the set of criteria initially adopted for the assessment of nuclear energy sustainability. As aforementioned, a safety indicator dealing with the impact of electricity generation on human health has been included. Global warming potential of considered policies has been introduced among the criteria applied in the assessment. It is an example of a global quantity included in the assessment of nuclear energy that could help in overcoming the limitation seen in the scope of the INPRO methodology for a more deep consideration of the dynamic principle as discussed in paragraph 2.3. Unit of measure and area of interest of the indicators employed for the assessment have been tailored as shown in Tab. 3.6.

In agreement with the INPRO methodology and based on the outlook period of interest a set of acceptance limits has been defined. Thanks to the scope of the analysis mostly devoted to mature and evolutionary systems, the framework proposed here appears to be closer than the GAINS Framework to a decision-making level. The framework has the potential to provide manageable and operational data for the discussion of medium-long-term energy policies. These objectives are fairly in agreement with the indications found in the literature regarding the objectives that a sustainable assessment should achieve.

Indicator Evaluation parameters	**Description**	**Area** Acceptance value
IND1	**Nuclear Power Production**	**Infrastructure**
EP.1	peak commissioning rate GW/yr)	40 GW/yr
IND2	**Nuclear Material Resources**	**Environment**
EP2.1	average net energy produced per % of consumed natural uranium (TWh/%proven resources)	average net energy produced per % of consumed coal resources
IND3	**Discharged Fuel**	**Infrastructure**
EP3.1	discharged fuel per GWa	INPRO methodology (IAEA, 2008b)
EP3.2	decay heat of waste (kW/GWa)	average value considering the historical development of nuclear energy
IND4	**Radioactive Waste**	**Environment**
EP4.1	radiotoxicity from inhalation and ingestion - (Sv/GWa)	average value considering the historical development of nuclear energy
IND5	**Fuel Cycle Services**	**Infrastructure**
EP5.1	additional resources in terms of percentage of current enrichment resources - 41850 tSWU/year as in (INFCIS, 2016)	50%
IND6	**Collective risk**	**Safety**
EP6.1	Years of Life Lost (YOLL) per TWh	coal reference (Köne and Büke, 2007)
IND7	**Cost of electricity**	**Economics**
IEP7.1	LUEC (mills/kWh)	coal figure of merit
IND8	**Attractiveness**	**Economics**
EP8.1	ROI (% per year)	coal figure of merit
EP8.2	NPV (USD/kWe)	coal figure of merit
IND9	**Affordability**	**Economics**
EP9.1	total investment (MUSD)	coal figure of merit
IND10	**Climate change mitigation**	**Environment**
EP10.1	100-year global warming potential (Mtonnes of CO_{2eq})	Current Policies Scenario, value in 2035 (IEA, 2013a)

Table 3.6: Key indicators and evaluation parameters included in the framework for the assessment of nuclear energy sustainability

The determination of the key indicators presented in Tab. 3.6 is carried out by means of DESAE 2.2 (Dynamics of Energy System of Atomic Energy, version 2.2). This tool has been developed by the Russian Kurchatov Institute (Andrianova et al., 2012; Tsibulskiy et al., 2006). The code, mainly conceived for its application within the activities of INPRO, has been included among the tools employed in a recent international benchmark (NEA, 2012b; IAEA, 2004; IAEA, 2008a).

DESAE has the capability to model both open and closed nuclear fuel cycles and to determine requirements, material flows and economic performance of a given combination of nuclear power plants, reprocessing plants and storage sites. The code may track independent fuel cycles in different regions simultaneously. Seven different types of nuclear power plant can be employed. Each plant is defined by means of a set of input parameters that may vary in the outlook period of the study. Plants' parameters are composed of different groups of data. A general section deals with information such as thermal capacity, thermal efficiency, construction time, plant lifetime, heavy metal loading of the reactor core. Following group of parameters deals with the use and consumption of materials required during construction and operation (e.g., water, aluminium, and zirconium). The content of ^{235}U in the tails of the enrichment process is included in this section.

Another set of data permits to track the economic performance. Costs of natural uranium, separative work unit (SWU), and fuel fabrication are included in this group. A more ample dataset is needed to describe the initial, equilibrium and spent isotopic composition of the reactor core. DESAE does not perform neutronic calculations to account for the isotopic change occurring in the fuel during irradiation.

In each scenario the fraction of electrical capacity of each type of nuclear fleet should be consistent with the total nuclear capacity requirement. In a closed fuel cycle, capacities and costs of reprocessing plants should also be introduced in the model. Calculations provide several outcomes such as the consumption of natural uranium, fuel loading rate, amount of nuclear spent fuel, consumption of zirconium, investment costs, and cost of energy.

The author has published some studies on different aspects of nuclear fuel cycles modeled by means of DESAE. They deal with the investigation on an Italian scenario (Calabrese, 2010; Vettraino and Calabrese, 2010) and a comparison of DESAE with the NFCSS code (Calabrese and Fesenko, 2011). NFCSS (formerly called VISTA) is a web-based tool developed by the IAEA that has capabilities close to those of DESAE (NFCSS, 2016). The author used DESAE to study the recycling of plutonium in light water reactors (Calabrese et al., 2011, Calabrese, 2013a) and minor actinides recycling in innovative fast reactors (Calabrese, 2013b). He took part in studies on the definition of scenarios for the development of sodium fast reactors (Bianchi et al., 2011). An interesting application of DESAE has been presented by Mohapatra and Mohanakrishnan (2010) where the code is applied in synergy with MESSAGE a tool by the IAEA to model the energy sector.

3.7 Final step of the assessment

ANP is used for the evaluation of the criteria presented in Tab. 3.6. Alternative scenarios are pairwise compared as shown in Fig. 3.6. This approach is more flexible than a plain compliance of criteria as done in the INPRO methodology. The INPRO methodology gives a judgment of sustainable vs. unsustainable. ANP provides a ranking of alternatives without exclusion to reinforce the debate and the discussion among stakeholders.

This choice gives the opportunity to the assessor to cluster criteria and to assign weights to them. This option is in better agreement with a closer consideration of the normativity and equity principles. Stakeholders can agree which are the prominent objectives to take into account in the assessment. In addition, the use of weights that account for the uncertainties affecting each indicator or group of indicators could introduce the adoption of a precautionary principle in the assessment in compliance with the dynamic principle.

A comparative assessment does not require the definition of specific acceptance limits that are more consistent with a concept of "best practice" and internally set by the INPRO methodology. This aspect will be discussed in paragraph 5.5.

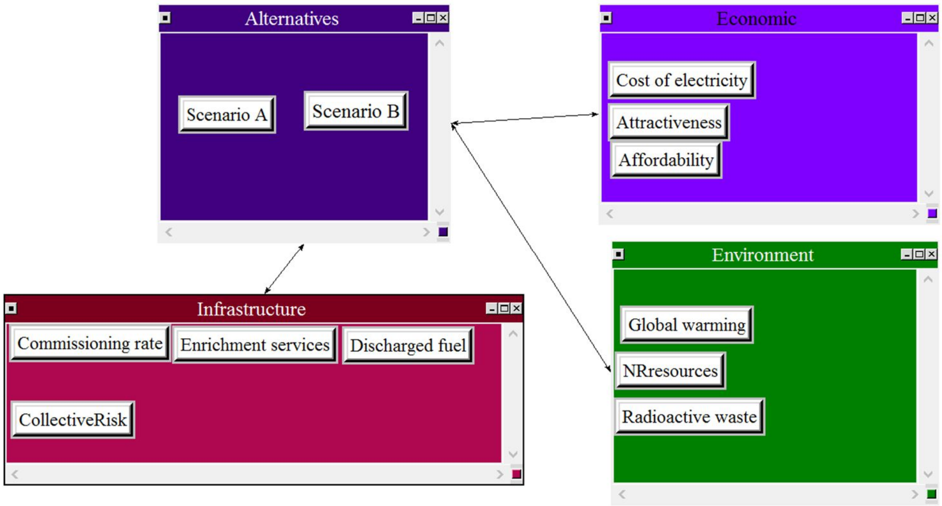

Figure 3.6: ANP model for the determination of scenarios' priorities (two alternative scenarios)

4. MODELING OF TECHNOLOGIES AND ADDITIONAL ASSUMPTIONS

4.1 Introduction

Based on a review of main specifications, in this chapter six electricity generating technologies are modeled. Great attention was focused on the economic performance of each technology and its projection in the outlook period. The overnight capital cost of nuclear energy and solar PV have shown significant changes in recent years. Onshore wind confirmed a decreasing trend of its capital cost, however, at a lesser extent than solar PV. Natural gas- and coal-fired plants confirmed costs generally stable in agreement with their technological maturity. In the literature, projections of costs are assumed to be stable in the long-term.

References have been collected at the end of the chapter.

4.2 Overnight capital cost

The data has been presented under the assumption that the construction of plant starts the year following its monetary unit, e.g., for values expressed in 2009 dollars construction and related costs are assumed to be referred to 2010.

The overnight capital cost of nuclear is presented in Fig. 4.1 Costs of nuclear energy increase in agreement with the hypothesis that the Fukushima accident could have given rise to an escalation in costs. In projections this trend is smoothed with values generally grouped around 6000 USD per kW. This could be reasonable noting that evolutionary nuclear systems should achieve a reduction in costs beyond 2030 thanks to learning. According to these considerations, the cost of nuclear energy could reach a maximum around 2030 at a level that at the current rate of increase should be close to 8000 USD per kW. It is worth reminding that highly standardized reactor types and markets may achieve a sharp reduction in costs as clearly presented in (IEA, 2014).

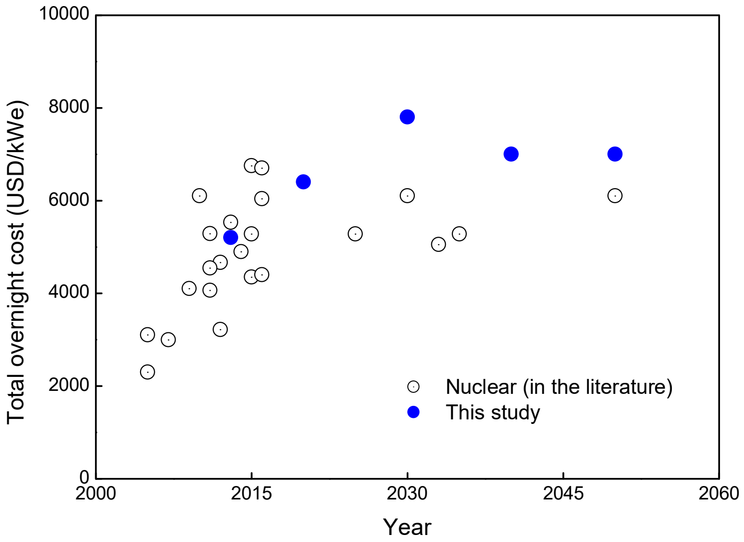

Figure 4.1: Nuclear - overnight cost

The overnight cost of solar PV (utility plants) shows a sharp decrease as resented in Fig. 4.2. The overnight cost of solar PV employed in this study has been resumed in Tab. 4.1. Most recent data shows a decrease more significant than predicted in previous studies. Cost projections adopted in the results presented here are fairly consistent with these recent indications.

The data on onshore wind confirms that this technology has already achieved a good level of maturity and margins for improvement are considered to be much narrower than in the case of solar PV. In Fig. 4.3 and Tab. 4.1 values found in the literature and adopted in this study are presented. The overnight cost of hydro is strongly dependent on each specific project. The data published in the literature (not shown) is mostly consistent with the indication reported in (NREL, 2012).

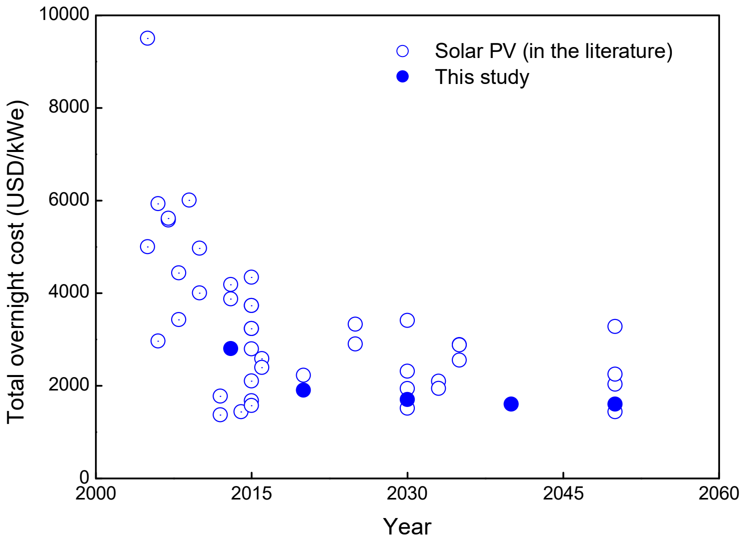

Figure 4.2: Solar PV - overnight cost

Indications found in the literature agree on the hypothesis that the overnight cost of coal- and natural gas-fired plants should slightly decrease in the future. Small deviations have been noted in this data.

Overnight costs are affected by inflation and escalation rate, these two factors have not been discussed in the results presented here.

Year	**2013**	**2020**	**2030**	**2040**	**2050**
Nuclear	5200	6400	8000	7000	7000
Solar PV	2800	1900	1700	1600	1600
Onshore wind	1850	1600	1580	1460	1460
Hydro	3500	3500	3500	3500	3500
Coal	2500	2470	2420	2400	2400
Natural gas	1050	1020	980	950	950

Table 4.1: Total overnight costs employed in calculations (USD/kWe)

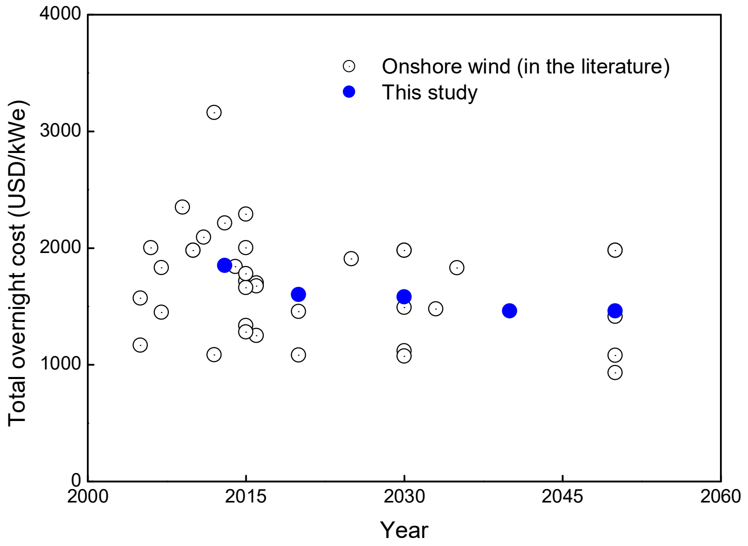

Figure 4.3: Onshore wind overnight cost

4.3 Fixed and variable O&M costs

In the case of nuclear energy, reviewed fixed O&M costs show an average value close to the indication found in (EIA, 2013). It has been assumed an increase up to 2030 consistent with the data found in the literature; see Fig. 4.4.

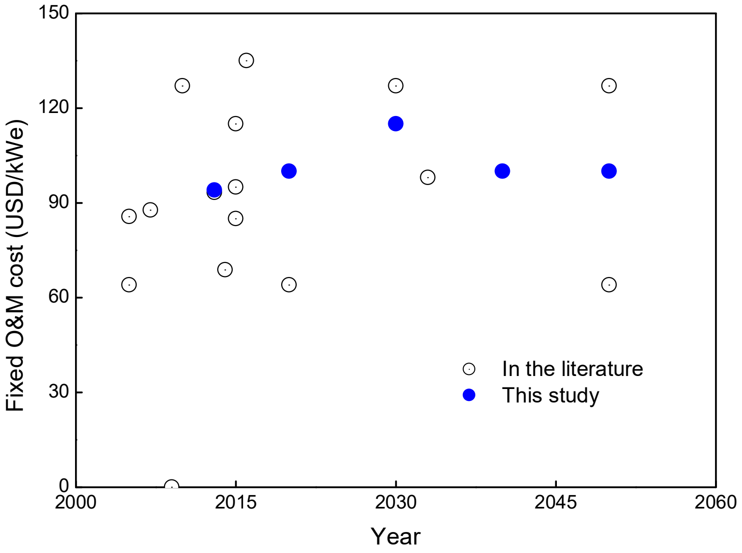

Figure 4.4: Fixed O&M cost of nuclear energy

The fixed O&M cost of solar PV shows a sharp decrease followed by smooth projections. Values adopted in our analysis are presented in Fig. 4.5 and in Tab. 4.2.

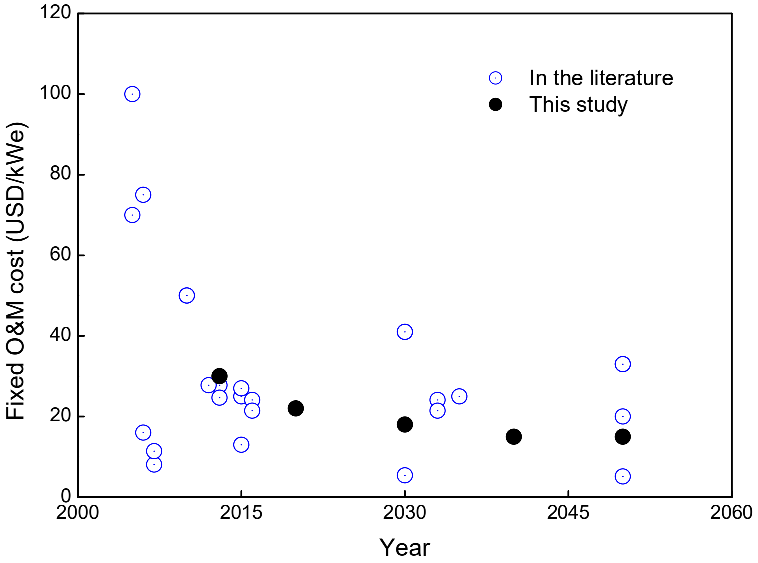

Figure 4.5: Fixed O&M cost of solar PV

The fixed O&M cost of onshore wind lies in the interval 20-60 USD per kWe. Some indications found in the literature have been discarded as obtained under the assumption that variable O&M costs are not null. Values used in the analysis have been determined under the hypothesis that the fixed O&M cost will decrease in the future at a lesser extent than in least conservative projections.

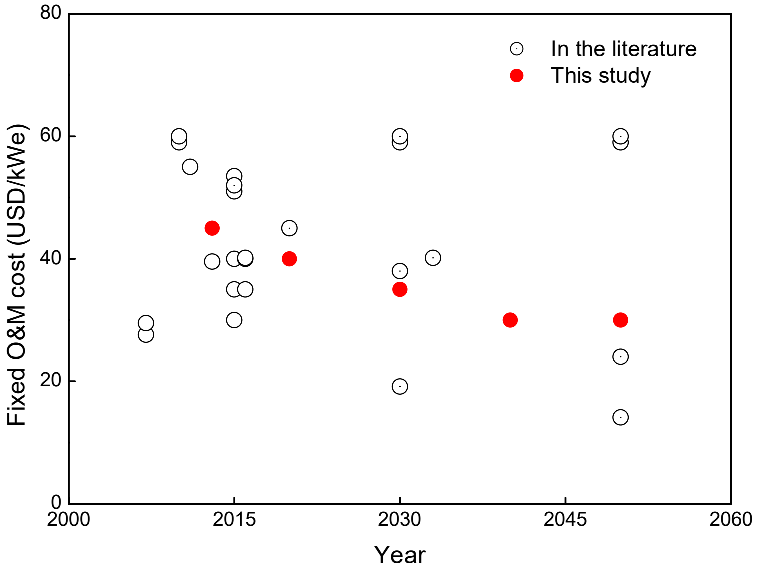

Figure 4.6: Fixed O&M cost of onshore wind

Fig. 4.7 shows the values of fixed O&M cost in coal-fired plants found in the literature. A certain scatter is noted in estimations of fixed costs up to 2015 with a peak value around 40 USD per kWe. Values adopted in this study are shown in the same figure and resumed in Tab. 4.2.

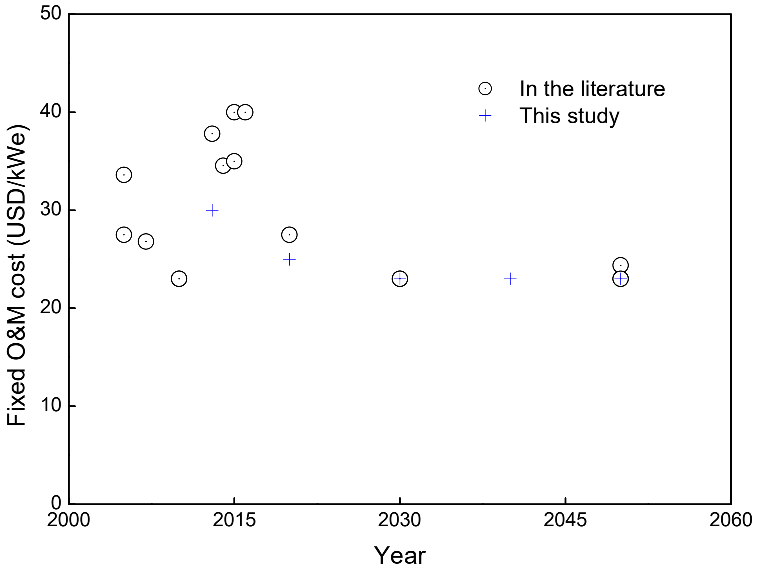

Figure 4.7: Fixed O&M costs in coal-fired plants

The fixed O&M cost of natural gas-fired plants applied in calculations is presented in Tab. 4.2. These values are consistent with the indications found in the literature and show a steady decrease in the outlook period. Some deviations have been noted in (IEA/NEA, 2015) that reports a value close to 30 USD per kWe in combination with a value of the variable O&M cost much lower than usually adopted. Finally, the O&M cost of hydro has been defined according to (NREL, 2012).

Year	**2013**	**2020**	**2030**	**2040**	**2050**
Nuclear	94	100	115	100	100
Solar PV	30	22	18	15	15
Onshore wind	45	40	35	30	30
Hydro	15	15	15	15	15
Coal	30	25	23	23	23
Natural gas	15	14	13	12	11

Table 4.2: Fixed O&M cost (USD/kWe-yr)

The values of variable O&M cost are presented in Tab. 4.3. They are fairly consistent with the indications found in the review. These assumptions have been maintained constant in the course of the outlook period.

Technology	**Nuclear**	**Hydro**	**Coal**	**Natural gas**
Variable O&M cost	2.14	6	5	4

Table 4.3: Variable O&M cost (USD/MWh)

4.4 Capacity Factor

The capacity factor is one of the most important quantities for the determination of the economic performance of electricity generating technologies. According to (IEA, 2014), values of capacity factors in the central scenario are practically constant for coal (54-58%), gas (40%), and hydro (39%). Nuclear improves from a value of 71% to 85%. This behavior is confirmed in (IAEA, 2015a). Improvements are expected in the case of onshore wind and solar PV (IEA, 2014). Their performance moves from 21% to 30% in the case of onshore wind and from 11.3% to 16% for solar PV. Most of the data found in the literature is consistent with these indications, however, in projections values around 40% are also adopted (ENEA, 2016), Most recent studies extend the improvement of capacity factor up to 40% in the case of onshore wind up to 25%-40% in solar PV (IRENA, 2015; Lazard, 2015; REN21, 2016). Values of capacity factor adopted in calculations are presented in Tab. 4.4.

Year	**2013**	**2020**	**2030**	**2040**	**2050**
Nuclear	80	85	85	85	85
Solar PV	12	22	24	25	25
Onshore wind	22	25	28	30	35
Hydro	50	50	50	50	50
Coal	60	60	60	60	60
Natural gas	40	40	40	40	40

Table 4.4: Capacity factors by technology in the outlook period (%)

4.5 Plant size

The size of nuclear power plants has been defined according to the indications reported in (IAEA, 2013b). Generation II and Generation III plants have a size of 1000 MWe and 1600 MWe, respectively. In solar PV technology, the size of utility plants spans from 1 up to 100 MWe. The onshore wind technology shows values in the interval 50-100 MWe. In both cases highest values have been adopted.

The size of coal-fired plants is in majority of reviewed data consistent with a value of 600 MWe. In gas-fired plants values in the interval 250-600 MWe have been reported. A value of 550 MWe has been adopted. In agreement with previous choices, in the case of hydro a large plant has been considered (500 MWe).

4.6 Thermal efficiency

In the central scenario of the IEA average thermal efficiencies generally improve in the outlook period (IEA, 2014). Coal moves from 33% to 37%, natural gas from 37.5% to 46.6%. The efficiency of nuclear energy is stable at 33% (IEA, 2014). Lowest values have been adopted in existing capacity while new plants should be featured by improved thermal efficiencies.

In calculations the efficiency of nuclear energy has been set to 33% in existing plants and 36% in evolutionary plants that should represent the additional nuclear capacity. Current natural gas-fired plants are mostly consistent with a standard technology with thermal efficiencies close to 40%. The capacity added in the course of the outlook period has a thermal efficiency near to 60% in agreement with the indications found in the case of CCGT plants (combined cycle gas turbine). Coal technology is characterized by a thermal efficiency of 37% increasing to 43% in new plants. The thermal efficiencies used in calculations are resumed in in Tab. 4.5.

Thermal efficiency (%)	**Existing capacity**	**New capacity**
Gas-fired power plants	40	55
Coal-fired power plants	37	43
Nuclear power plants	33	36

Table 4.5: Thermal efficiencies (%)

4.7 Plant lifetime

Based on the results of review, the plant lifetimes adopted in modeling are:

Wind and solar plants	25 years;
Gas-fired power plant	30 years;
Coal-fired power plant	40 years;
Nuclear power plant	60 years;
Hydro	50-80 years.

The lifetime of generation II power plants (existing technology) has been assumed to be 50 years.

4.8 Construction time

The construction time or lead time is a relevant factor in the evaluation of the financial resources required to deploy a specific technology. Following assumptions have been employed in modeling:

Non-hydro renewables	1 year;
Hydro	3 years;
Gas-fired power plant	3 years;
Coal-fired power plant	4 years;
Nuclear power plant	6 years.

4.9 Additional assumptions

4.9.1 Retirement curves of existing capacity

How the existing electrical capacity is retired in the course of the outlook period is certainly important for the implementation of new energy policies. The retirement curve of a specific technology depends on the level of installed capacity in the base year and the lifetime of plants. In more detail, the rate of addition before the base year is relevant to properly consider its retirement in the first part of the scenario.

The curve of nuclear capacity retirements has been defined in agreement with its historical evolution in the years 1960-2013 (IAEA, 2013b; IAEA, 2015a).

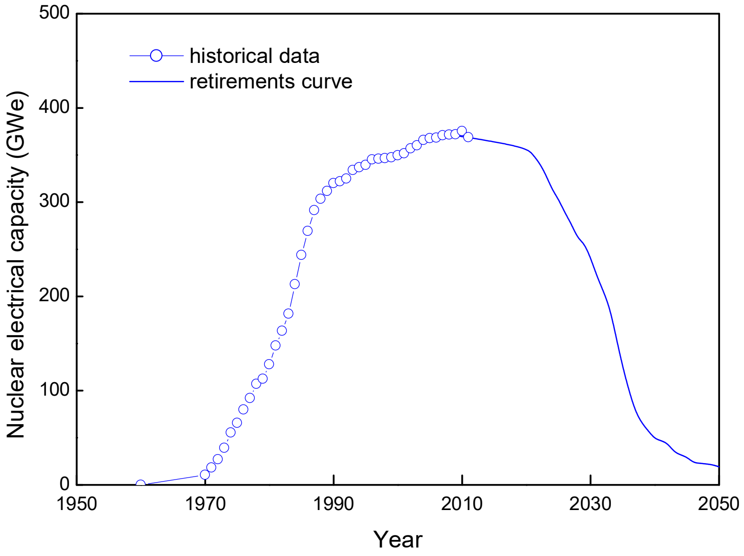

Figure 4.8: Historical development and retirement curve of nuclear electrical capacity

Tab. 4.6 resumes the hypotheses considered in calculations in the case of non-nuclear technologies. The capacity of hydro in the base year has been maintained unchanged in the course of the outlook period without considering the occurrence of retirements.

Energy source	**Rules adopted for retirement**
Coal	Linear retirement consistent with plant lifetime
Gas	Linear retirement consistent with plant lifetime
Hydro	No retirement
Wind	Constant up to 2020; 2020-2030 linear retirement
Solar PV	Constant up to 2020; 2020-2030 linear retirement

Table 4.6: Rules adopted in calculations for the retirement of the electrical capacity installed in the base year

Fig. 4.9 shows the increasing gap between demand and production of electricity if current capacity retires according to previous rules and no new capacity is added. The growth in demand is +2.2% per year. Significant resources are needed, however, this condition is a good opportunity to redefine the energy mix according to the indications of stakeholders.

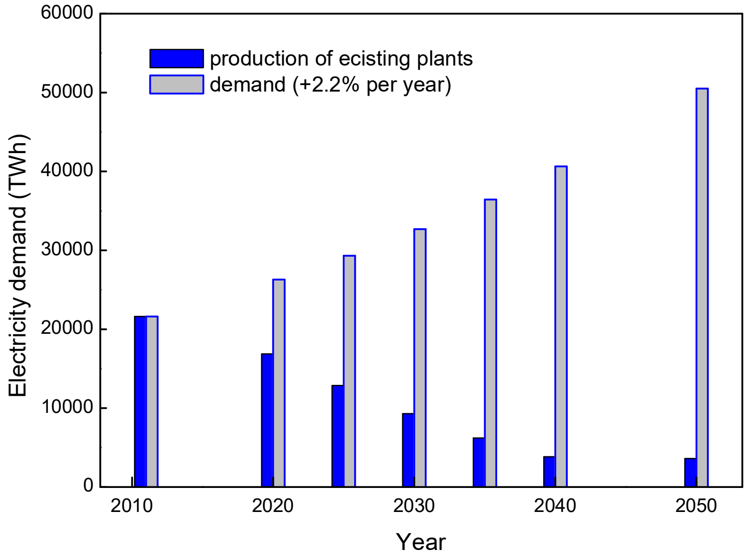

Figure 4.9: Electricity needs (+2.2 %/year) vs. existing capacity contribution

4.9.2 Decommissioning costs, price of electricity

Costs of decommissioning at the end of plant lifetimes have been assumed to be 15% and 5% of the overnight cost in nuclear and non-nuclear technologies, respectively (IEA/NEA, 2010; IEA/NEA, 2015).

The price of electricity is 120 mills/kWh. This choice has been based on a qualitative evaluation of the projections published in (IEA, 2013a; IEA, 2014).

4.9.3 Fuel price

In (IEA/NEA, 2010) the price of fossil fuels was (2009 dollars):

Coal (OECD member countries):	USD 90 per tonne;
Natural gas (OECD Europe):	USD 10.3 per MMBtu;
Natural gas (OECD Asia):	USD 11.7 per MMBtu.

In 2013, the price of natural gas was 2.43 and 3.71 USD per MMBtu in the USA and Canada, respectively (BP, 2014). This parameter was 10.72 and 10.73 USD per MMBtu in Germany and UK with a peak in Japan where the price of gas reached a value of 16.17 USD per MMBtu. Similarly, the price of steam coal was 111.16 USD per tonne in Japan versus values of 71.39 in the USA and 90.90 in the Asian market (BP, 2014).

Following prices expressed in 2013 dollars have been reported in (IEA/NEA, 2015):

Coal (OECD member countries): USD 101 per tonne;
Natural gas (OECD Europe): USD 11.1 per MMBtu;
Natural gas (OECD Asia): USD 14.4 per MMBtu.

This report points out that in the second half of 2014 fuel prices showed significant declines globally (IEA/NEA, 2015). As already stated in (IEA/NEA, 2010), if on the one hand the use of LCOE is certainly important in the analysis of generation costs, on the other hand the real market place is much more complex and characterised by multiple risks and uncertainties not accounted in the LCOE methodology.

The price of natural gas was 9.11 and 8.22 USD per MMBtu in Germany and UK with a peak in Japan that accounted for a value of 16.5 USD per MMBtu. Similarly, the price of steam coal was 114.41 USD per tonne in Japan versus values around 69 USD per tonne in the USA (BP, 2015).

In the frame of the Italian energy sector, some international statistics are reported in (MSE, 2016). Useful information regarding the trend of primary energy prices is given confirming that they showed a sharp decrease in comparison with previous years. This has been mostly explained by the significant reduction seen in the price of oil. A corresponding noticeable increase in the consumption of oil has been recorded in 2015. According to the Henry Hub, he average cost of natural gas was in 2015 2.6 USD/ MMBtu. In Europe, the price of natural gas has recorded a value of 6.5 USD/ MMBtu.

In recent data published by Platts (2015), the price of 5500 kcal/kg Net Calorific Value coal stands in the interval 40-50 USD per tonne. As of August 2016, the price of Central Appalachia coal was 43.30 per tonne while the price of US natural gas was 2.76 USD per MMbtu (EIA, 2016).

Therefore, the declining trend of fuel prices mentioned in (IEA/NEA, 2015) is still ongoing. Shafiee and Topal (2010) affirm that the global financial crisis occurring in 2008 was partly due to the escalation of fuel prices since 2003. Authors note a correlation between oil price and natural gas price. The historical data has shown an increase in natural gas price and a decrease in coal price if compared to oil. The existence of these correlations further confirms that assumptions on the price of fuels in 2020 and beyond are a significant source of uncertainties.

In the results presented in chapter 5, high fossil fuel costs have been assumed under the hypothesis that they will see a rebound to pre-2014 levels. This condition is favorable for a transition to low carbon electricity generation. These assumptions are listed below:

coal	USD 90 per tonne (25.71 USD/MWh);
natural gas	USD 10.5 per MMBtu, (65.14 USD/MWh).

In agreement with recent indications that assume a sharp reduction in the price of fossil fuels and in compliance with the hypothesis that fuel prices remain low and stable, following values have been employed in the results presented in chapter 6:

coal	USD 60 per tonne, (17.14 USD/MWh);
natural gas	USD 5.5 per MMBtu, (34.12 USD/MWh).

Values written in brackets have been calculated by employing aforementioned thermal efficiencies and the conversion factors published in (IEA, 2016). Pairwise comparisons and weights assigned to non-economic indicators are expected to smooth the effect of fuel prices volatility.

4.9.4 Nuclear fuel cost

The cost of nuclear fuel should account for the expenditures required both in the front-end and in the back-end of a nuclear fuel cycle. The processes carried out in the front-end are: extraction, conversion, enrichment, fuel fabrication. Similarly, in an open fuel cycle the back-end includes interim dry storage and final geological disposal. In order to express the cost of fuel in terms of electricity produced it is necessary to consider the cost of each stage as well as plant-related parameters such as the content of ^{235}U in fresh fuel. Table 4.7 resumes some cost estimations referring to the front-end stages of an open fuel cycle.

Estimations regarding the cost of back-end have been published in (NEA, 2013b). This document gives indications laying in the interval 100-200 USD per kg$_{HM}$ and 225-1000 USD per kg$_{HM}$ for interim and geological disposal, respectively.

	Rothwell, 2010	**IAEA, 2014b**	**Rothwell and Ganda. 2014**	**WNA, 2016**
Natural uranium (USD/kg$_{HM}$)	206	70	105	97
Conversion (USD/kg$_{HM}$)		10		16
Enrichment (USD/SWU)	130	150	100	82
Fuel fabrication (USD/kg$_{HM}$)	250	300	300	300

Table 4.7: Front-end costs of nuclear fuel cycle

Evaluations on the fuel cost of generation II and generation III light water reactors are reported in Tab. 4.8. Back-end costs are 200 USD/kg$_{HM}$ and 1000 USD/kg$_{HM}$ for interim and geological disposal, respectively. Plant specifications are consistent with the models employed in DESAE calculations. Resulting values are consistent with the indications published in (IEA/NEA, 2015).

Light water reactor models	**Generation II**	**Generation III**
Capacity (GWe)	1.0	1.6
Efficiency (-)	0.33	0.36
Fuel loading (t_{HM})	78.653	133
Fuel in-core residence time (EFPD)	1168	1855
^{235}U content in NU (-)	0.00711	0.00711
Tail assay in depleted uranium (-)	0.003	0.003
Quantity for 1 kg_{HM} of nuclear fuel^		
Natural uranium (kg_{HM})	9.54	11.87
Conversion (k_{HM})	9.09	11.30
SWU	5.33	7.07
Fuel fabrication	1	1
Fuel cost (USD per kg_{HM})	1808.28	2211.90
Front-end cost (USD per MWh)	5.07	4.13
Fuel cost (front-end & back-end) (USD per MWh)	8.44	6.37

^ Values calculated according to the tool in http://www.wise-uranium.org/nfcm.html

Table 4.8: Fuel cost in generation II and III plants (WNA, 2016; Tab. 4.7)

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Note

References IEA/NEA, 2010; IEA/NEA, 2015; NREL, 2012c are also reported in the general REFERENCES section.
Reference EIA, 2016 in this section and in the general REFERENCES section do not coincide.

5. VERIFICATION OF THE METHODOLOGY

5.1 Introduction

The objective of this chapter is to verify if the indications provided by the layout discussed in chapter 3 are consistent and capable to properly describe the evolution of the power sector and the quantities relevant in the assessment of nuclear energy sustainability. For the purpose, the initial paragraph presents a validation of the economic parameters. Thereafter, the central scenario in (IEA, 2013a) has been implemented and extended up to the middle of the century to verify if the outcomes of the methodology are consistent with the reference and complying with a given policy. In the concluding pat of the chapter further considerations are given on the interpretation and use of the outcomes of ANP especially in regard to the final part of the assessment.

5.2 Verification and validation of the economic estimations

The validation of the NEST code modified as described in chapter 3 has been performed on the values of LUEC published in (IEA/NEA, 2010). Input parameters adopted in calculations are referring to the detailed description of the the median plants (IEA/NEA, 2010). Results are presented in Fig. 5.1.

Estimations showed a good accuracy in the case of coal and onshore wind. Some deviations have been noted in nuclear results especially under the hypothesis of 10% discount rate. This was mainly due to the assumption that the lead time is 6 years instead of 7 years as adopted in (IEA/NEA, 2010). A slight underestimation has been noted in the gas-fired plant with a negligible effect of the discount rate. Small deviations have been recorded in solar PV with 404.74 and 612.26 mills per kWh in the case of 5% and 10% discount rate, respectively.

The performance of NEST showed to be fairly constant notwithstanding the significant differences of the plants considered for validation. In addition, the accuracy of LUEC, ROI, and total investment estimations has been verified with the data reported in (IAEA, 2014b). Overall, a satisfactory agreement was proved with deviations acceptable for the objectives of this study.

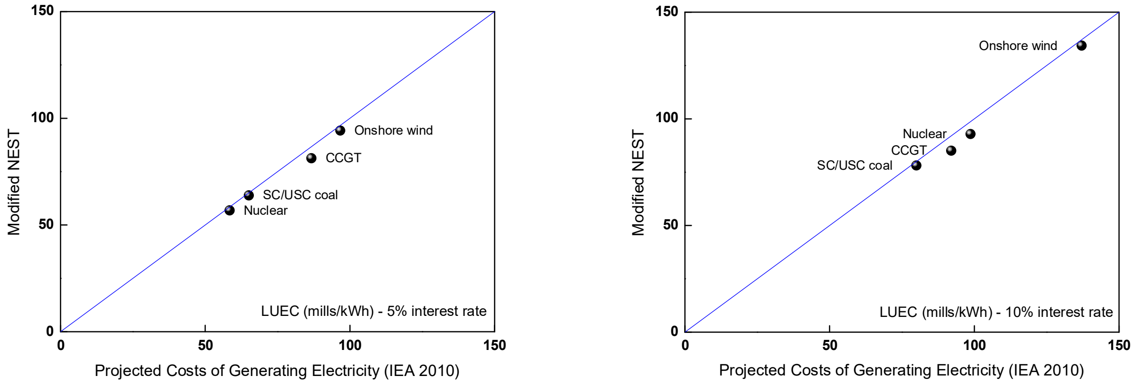


Figure 5.1: Comparison of LUEC calculations (IEA/NEA, 2010)

5.3 Description of the scenarios used for verification

The New Policy Scenario published in (IEA, 2013a) has given a good opportunity to have extensive information on a scenario validated up to 2035. In the second part of the outlook period that is up to 2050, 2 alternative hypotheses have been considered. In the first, the generation from coal-fired plants is increased to meet the share of demand left unmet because of the phase out of nuclear energy (Scenario A). In this scenario the construction of new nuclear power plants is not foreseen in the second part of the outlook period. The second policy considers a significant expansion of nuclear energy that permits to reduce accordingly the generation from coal-fired plants (Scenario B). Remaining electricity generating technologies move along trajectories that are broadly consistent with the projections adopted in the IEA analysis (IEA, 2013a). This construction has a two-fold objective: in the first part we are able to verify the outcomes of the framework against consistent and validated data; in the second part we assess if the layout is capable of correctly interpreting two quite different policies.

The base year is 2011. Simulations start in 2012 and end in 2050. The growth in electricity demand is +2.2% per year (IEA, 2013a). Scenarios include six types of electricity generating plants as presented in previous chapter. According to the historical trend discussed in (IEA, 2015), the role of oil-fired technology is foreseen to diminish further in the outlook period. The electricity production of oil-fired plants has been fictitiously taken into account by increasing the electrical capacity of coal-fired generation.

Some further hypotheses complete the analysis presented here:

- share of hydro remains nearly constant;
- natural gas increases in agreement with projections up to the middle of the century;
- electrical generation from renewable moves from 10% in 2035 up to 15% in 2050;
- share of nuclear moves in the interval 5-15%.

Fig. 5.2 and 5.3 show the generation mix assumed in Scenario A and Scenario B. The initial conditions assumed in calculations are presented in Tab. 5.1

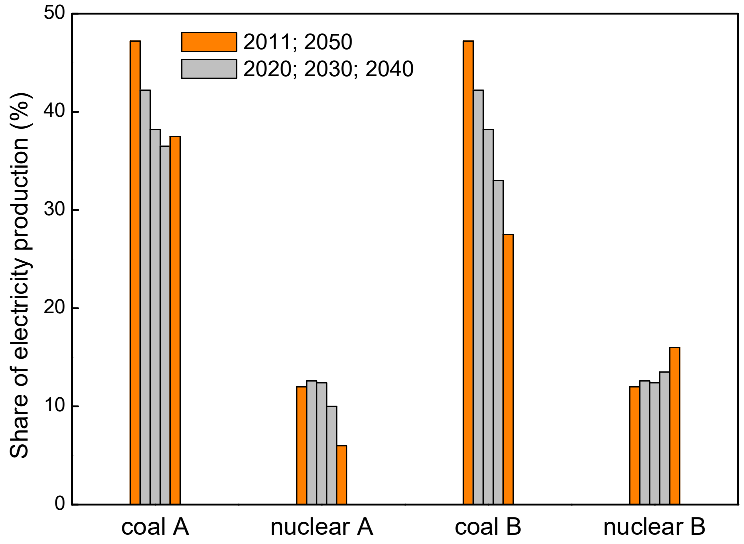


Figure 5.2: Nuclear vs. coal (values in 2011, 2020, 2030, 2040, and 2050)

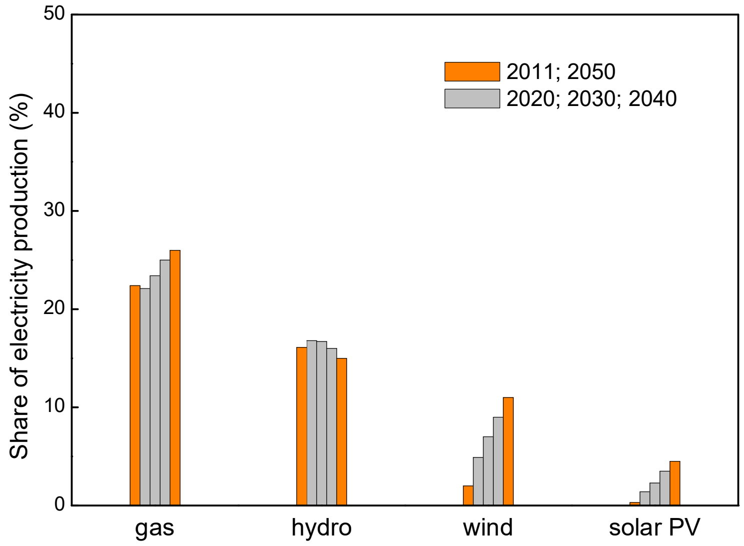


Figure 5.3: Generating technologies in both scenarios (values in 2011, 2020, 2030, 2040, and 2050)

	coal	**gas**	**nuclear**	**hydro**	**wind**	**solar PV**
Capacity (GW)	2178	1414	368	1060	238	69
Generation (TWh)	10201	4847	2584	3490	434	61

Table 5.1: Electricity generation and electrical capacity in 2010

The total electricity production accounted in the base year is 21617 TWh with an installed capacity of 5327 GWe. The power mix of Scenario A and B has been shared between exogenous and endogenous capacity according to the rules discussed in paragraph 4.9. Tables 5.2 and 5.3 resume the shares of electricity demand in the exogenous and endogenous capacity, respectively.

Year	2011	2020	2025	2030	2035	2040	2050
coal	47.2	26.8	18	10.8	4.8	0.0	0.0
gas	22.4	12.7	5.9	1.8	0.3	0.0	0.0
nuclear	11.9	9.5	7.2	5.1	2.4	0.8	0.3
hydro	16.1	13.3	11.9	10.7	9.6	8.6	6.9
wind	2.0	1.7	0.7	0.0	0.0	0.0	0.0
solar PV	0.3	0.2	0.1	0.0	0.0	0.0	0.0

Table 5.2: Exogenous capacity contribution to meet demand (%)

Calculations have been performed under the hypothesis that the planning reserve margin moves from a value of 75% in 2011 to 92% in 2050 to markedly reduce the unmet demand. The load curve has been defined by assigning a value expressed as percentage of the peak load in each period of the year (slice). In this analysis, the average load factor has been 81%. The discount rate adopted in calculations was 5%. Dispatching is ruled by the share of demand that each technology is expected to provide at the time concerned. The endogenous capacity has been added according to the shares given in Tab. 5.3 for Scenario A and corresponding quantities in Scenario B.

Year	2011	2020	2025	2030	2035	2040	2050
coal	0.0	15.4	21.9	27.4	31.9	36.5	37.5
gas	0.0	9.4	17.1	21.6	23.4	25.0	26.0
nuclear	0.0	3.0	5.4	7.3	9.8	9.2	5.7
hydro	0.0	3.5	4.8	6.0	7.0	7.4	8.1
wind	0.0	3.2	5.3	7.0	7.9	9.0	11.0
solar PV	0.0	1.2	1.8	2.3	2.7	3.5	4.5

Table 5.3: Scenario A: endogenous capacity contribution to meet demand (%)

5.4 Internal and external verification

A series of comparisons has been performed to verify the results provided by the codes employed in the methodology. Comparisons against reference data (external) and between tools (internal) are presented. In particular, it has been verified the consistency of LEAP and DESAE.

In Figures 5.4 and 5.5 the results of our analysis are compared with the data published in (IEA, 2013a). A reasonable agreement of LEAP with the indications found in the literature is noted. Bioenergy has not been considered in this analysis. This type of technology accounts for nearly half of the deviations seen in Fig. 5.4. The electrical capacity is in better agreement given the much lower importance of these plants. Results confirm that a combination of exogenous and endogenous capacity fits for the purpose of describing corresponding quantities in studied scenarios. The consistency among generation, capacity factor, and installed capacity is correctly implemented in the framework. In general, the modeling of technologies confirms to be consistent with the description given in the IEA analysis.

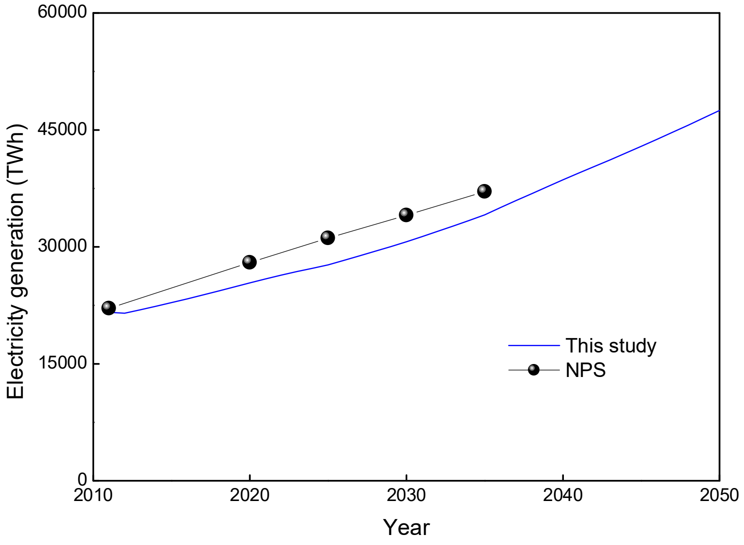


Figure 5.4: Electricity generation vs. NPS data

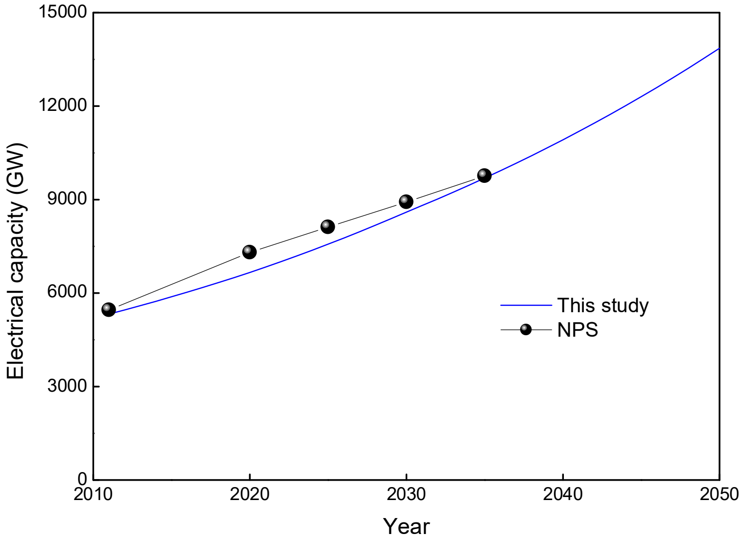


Figure 5.5: Electrical capacity vs. NPS data

In Figures 5.6 and 5.7 a comparison of electricity generation by technology with the data published in the reference is presented (Scenario A). Calculations are fairly consistent with (IEA, 2013a). The production from coal-fired plants deviates from the reference curve showing a steeper rate of increase in the concluding part of the outlook period; see Fig. 5.6. The generation of electricity from nuclear reaches a peak around 2030 thereafter its contribution begins a decline down to its initial value. These results are consistent with the policy implemented in Scenario A.

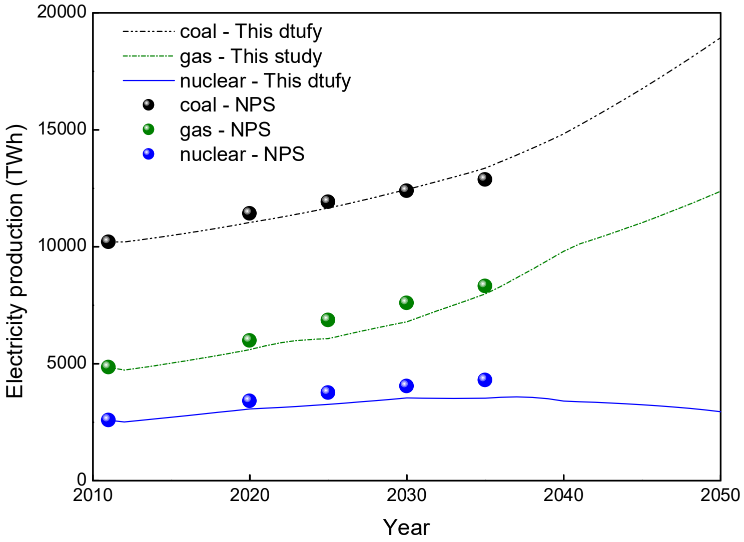


Figure 5.6: Electricity generation by technology vs. NPS data

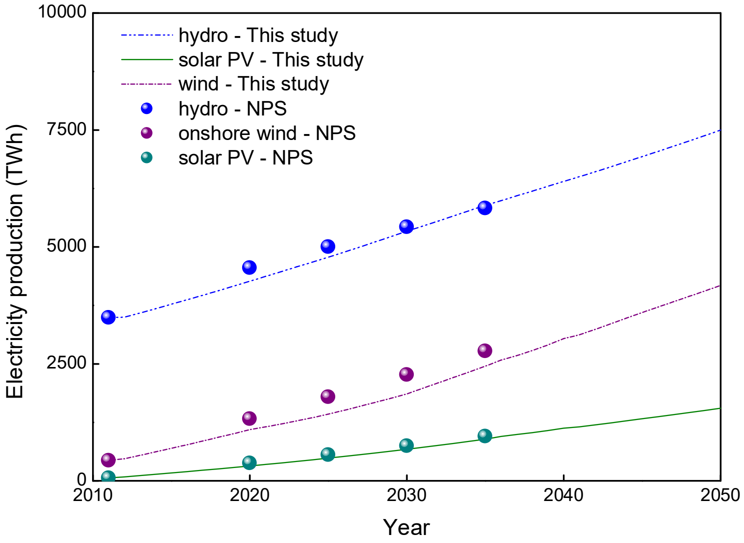


Figure 5.7: Electricity generation by technology vs. NPS data

The electrical capacity calculated by means of LEAP and corresponding NPS data are shown in Fig. 5.8 and 5.9. Notwithstanding some deviations are seen in the case of onshore wind, estimations are in good agreement with NPS. In scenario A, no additional nuclear capacity is installed beyond 2040 to maintain its capacity factor at a level reasonably high. In coincidence of the stagnation of nuclear capacity, the capacity of coal-fired plants clearly deviates from the trajectory figured out in the New Policies Scenario. The total capacity of natural gas plants gets close to the level of coal-fired plants by 2040.

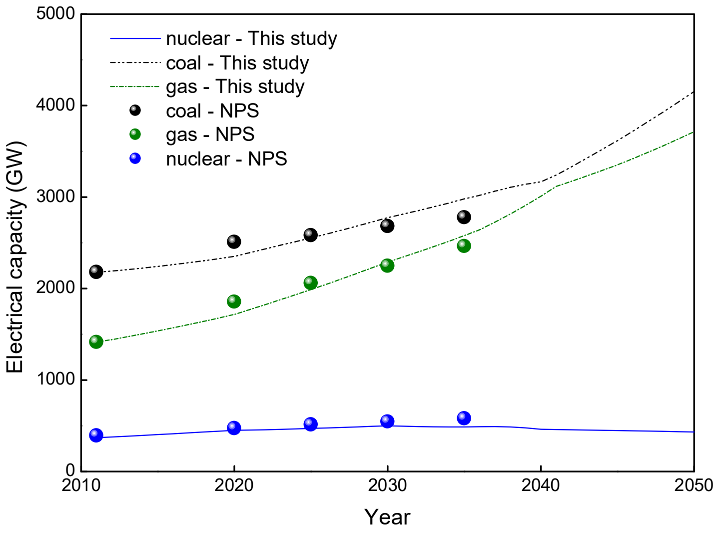


Figure 5.8: Electrical capacity by technology vs. NPS data

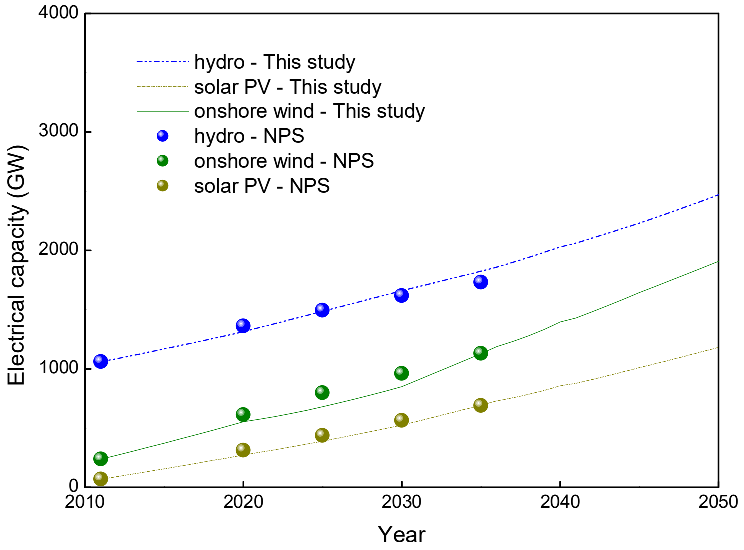


Figure 5.9: Electrical capacity by technology vs. NPS data

Overall, these outcomes prove to be in satisfactory agreement with the projections and confirm that the models of electricity generating technologies are quite consistent with a validated framework such the IEA's one. Results seen in the concluding part of the outlook period confirm the capability of this layout to correctly implement a given policy.

Emissions by fuel are are presented in Fig. 5.10. The effect under consideration is the 100-year global warming potential due to the emissions of greenhouse gases (CO_2, NO_2, CH_4). In Scenario A, total emissions increase beyond 20000 Mt. The largest contribution is due to coal-fired plants. The fictitious coal-fired capacity properly accounts for the emissions of oil-fired plants not included in the power sector model. Calculations are in good agreement with the data published in (IEA, 2013a).

The addition of coal-fired electrical capacity in the place of oil-fired is correct as confirmed by the estimation of primary energy needs; see Fig. 5.11. In scenario A, the cumulative consumption of coal and natural gas amounts to 127338 and 62414 Mtoe, respectively. These values correspond to 181.9 billion tonnes of coal equivalent and 2.613 EJ of natural gas. By considering a gross calorific value of 39500 kJ per cubic meter, the resulting natural gas consumption corresponds to 73.5 trillion cubic meters (IEA, 2015). Proven resources are 1040 billion tonnes in the case of coal. Natural gas resources are 211 trillion cubic meters (IEA, 2013a). Therefore, in Scenario A the consumption of coal corresponds to 17.5% of proven reserves while this quantity gets about 35% in the case of natural gas.

Results confirm that the modeling of environmental impacts (global warming potential) and consumption of primary energy resources are in good agreement with the indications given by the IEA. Models of electricity generating technologies are therefore verified with regard to their GHG emissions and consumption of primary resources. These factors are strongly related to the thermal efficiency and the capacity factor of technologies.

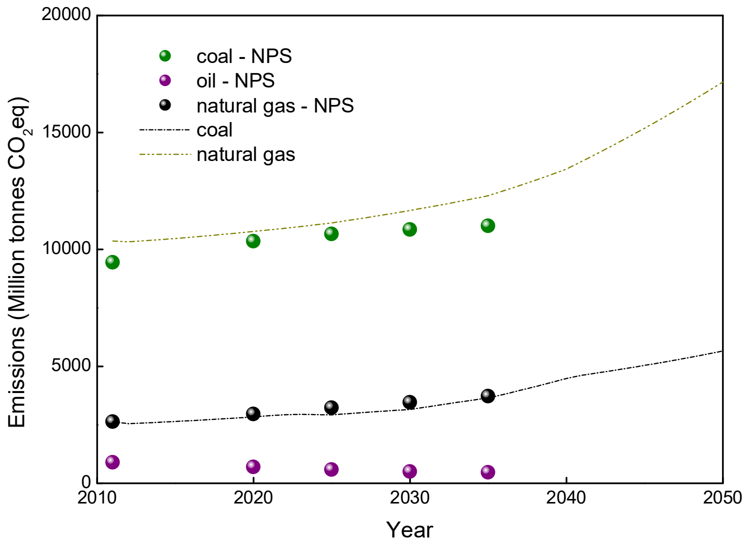


Figure 5.10: CO_2eq emissions by fuel (Scenario A)

DESAE calculations indicate that in Scenario A the consumption of natural uranium amounts to 5.536 million tonnes. Overall, resources of natural uranium (in the category < USD 260/kgU) amount to 7.6352 million tonnes (NEA/IAEA, 2014). Even at a moderate increase in nuclear energy as in the case of Scenario A the depletion of proven resources is 72.5%.

Table 5.4 resumes the primary energy requirements by scenario expressed in terms of proven resources (%) (IEA, 2013a; NEA/IAEA, 2014). It is worth reminding that coal and natural gas are not used only for electricity production as in the case of natural uranium.

Results on the need for primary energy supplies are consistent. The methodology proposed here is therefore capable of providing and considering relevant information for the assessment of energy resources sustainability. Outcomes correctly represent a significant increase in coal consumption, however, thanks to the improvement of thermal efficiencies the energy intensity of power sector is markedly ameliorated.

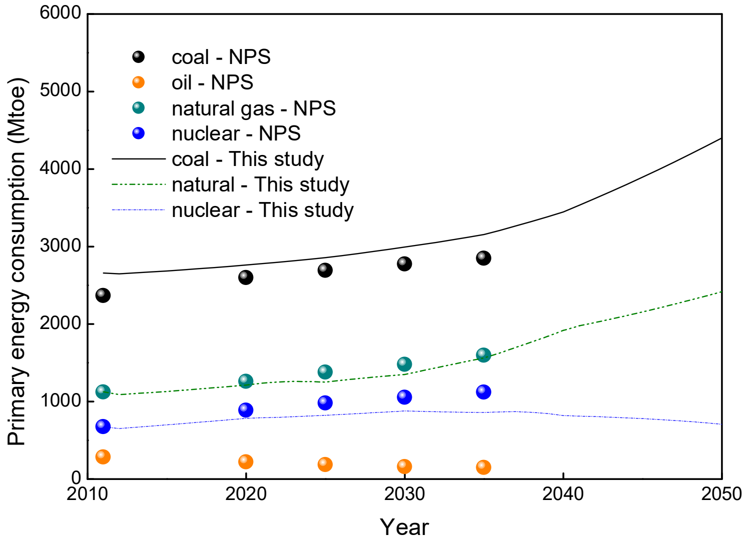


Figure 5.11: Primary energy consumption vs. NPS data

Primary energy needs (% proven resources)	**coal**	**natural gas**	**natural uranium**
Scenario A	17.5	35.0	72.5
Scenario B	16.3	35.2	88.6

Table 5.4: primary energy requirements (IEA, 2013a; NEA/IAEA, 2014)

Fig. 5.12 and 5.13 show the results of LEAP and DESAE dealing with the production of electricity from nuclear and the corresponding electrical capacity. Calculations are in good agreement with deviations mostly due to the capacity factor. In DESAE this quantity is an input parameter defined before calculations are performed, in LEAP the capacity factor is calculated by the code in compliance with an upper bound defined by the user (maximum availability). Provided that the electrical capacity and capacity factor calculated by LEAP are properly introduced in DESAE, calculations are expected to be in quite good agreement. Quantities specific of the nuclear fuel cycle considered in the analysis are therefore included in the assessment in a consistent manner.

Fig. 5.14 presents the cost of nuclear fuel in Scenario A (endogenous capacity). While in LEAP fuel costs are lumped in a single parameter, DESAE calculates the cost occurring in each process of the fuel cycle. O&M costs are presented in Fig. 5.15. The LEAP code provides evaluations on the variable and fixed component of O&M costs while the DESAE model gives a single value that includes both contributions. Codes' predictions prove to be in reasonable good agreement.

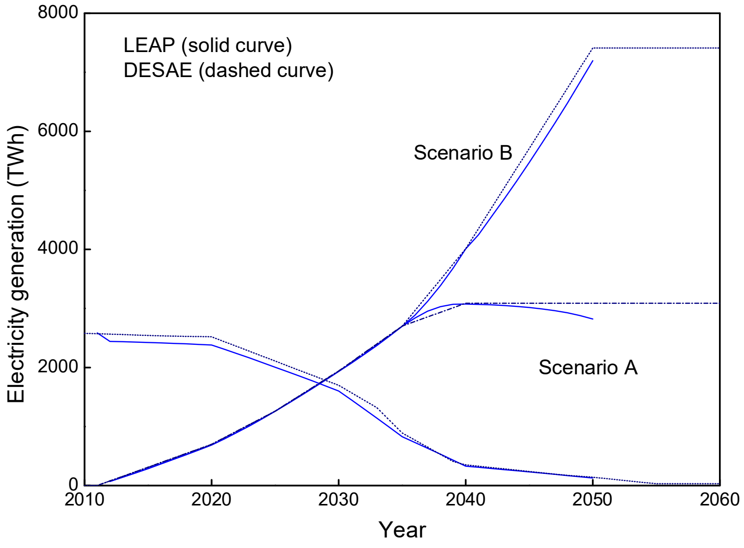


Figure 5.12: Electricity generation (Scenario A & Scenario B)

Models of electricity generating technologies have proven to be fairly consistent with the IEA description of the power sector. Verifications on aspects dealing with the economic behaviour, technical performance, GHG emissions, and use of primary resources confirm that the framework is capable to provide a realistic and consistent modeling of the power sector and involved technologies.

The DESAE code confirms to be capable to provide information consistent with the scenarios of power generation allowing to focus the analysis on the the modeling and performance of nuclear fuel cycle.

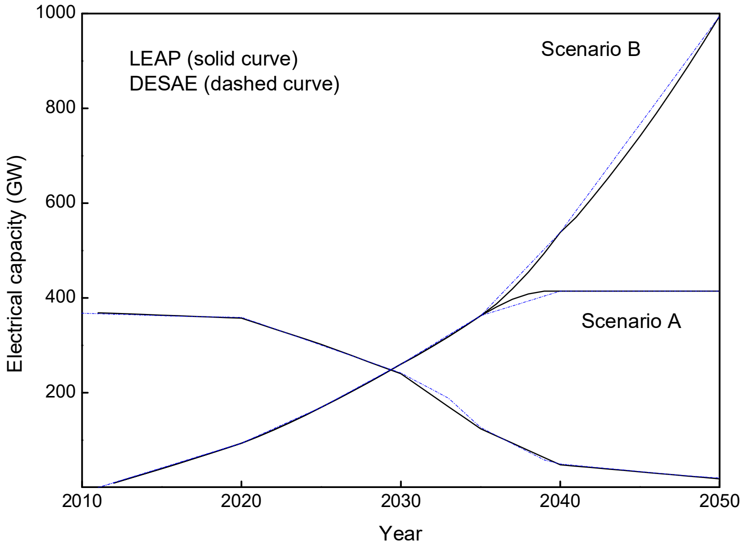


Figure 5.13: Electrical capacity (Scenario A & Scenario B)

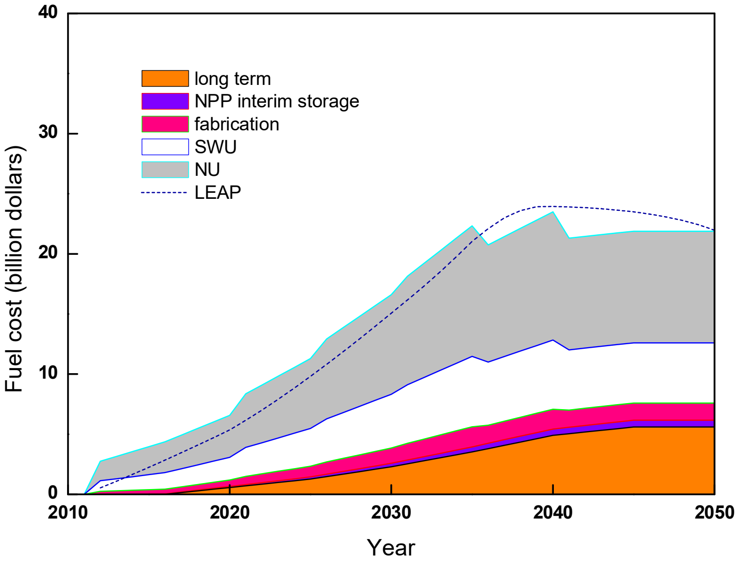


Figure 5.14: Fuel cost (nuclear endogenous capacity - Scenario A)

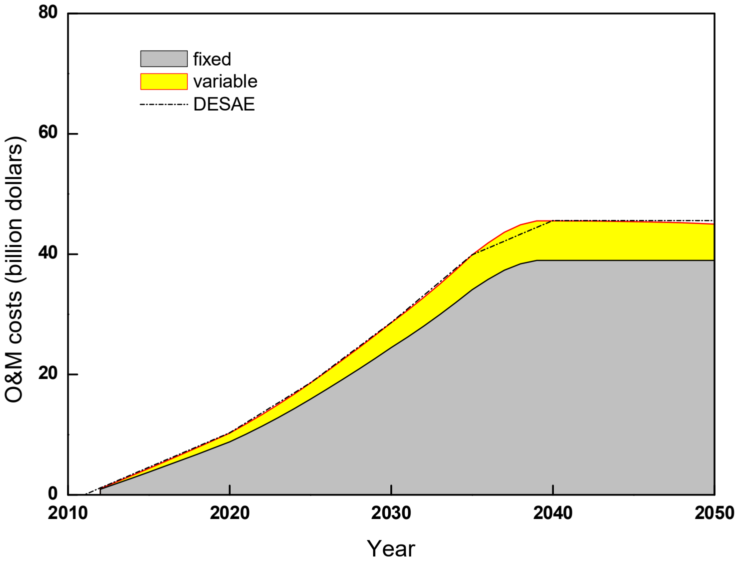


Figure 5.15: O&M cost (nuclear endogenous capacity - Scenario A)

5.5 Sustainability assessment of nuclear energy

Based on the outcomes presented in previous paragraph, indicators and acceptance limits chosen for the assessment of nuclear energy sustainability have been calculated. Results are presented in Tab. 5.5.

Tab. 5.5 summarizes which indicator complies with the acceptance limit and which one does not meet the corresponding limit (success vs. failure). Intermediate results by area and the concluding outcome of the assessment are reported in Tab. 5.5 as well.

Evaluation parameters	**Scenario A**	**Scenario B**	**Acceptance Limit**
NuclearPower Production	**success**	**failure**	
EP1.1 (GW/yr)	20.42	45.64	40
Nuclear Material Resources	**failure**	**failure**	
EP2.1 (TWh/%NRR)	2910.6	2652.2	30266.2
Discharged Fuel	**success**	**success**	
EP3.1 (tonne/GWa)	20.69	18.00	30.0
EP3.2 (kW/GWa)	30.1	40.8	63.2
Radioactive Waste	**success**	**success**	
EP4.1 (Sv/GWa)	3.533e+08	3.207e+08	3.212e+08
Fuel Cycle Services	**success**	**failure**	
EP5.1 (% of proven resources)	+27%	+74%	+50%
Safety	**success**	**success**	
EP6.1 (YOLL/TWh)	11.9	11.9	165.5
Cost	**success**	**success**	
EP7.1 (mills/kWh)	60.7	60.7	70.7
Attractiveness	**success**	**success**	
EP8.1 (% per year)	13.6	13.6	17.7
EP8.2 (USD/kWe)	10283	10283	5663
Affordability	**failure**	**failure**	
EP9.1 (MUSD)	10911	10911	1675
Climate change mitigation	**failure**	**success**	
EP10.1 (Mtonne of $CO_{2\text{-eq}}$)	22811	18353	19123
Infrastructure (% of criteria)	100	33	
Environment (% of criteria)	33	66	
Economics (% of criteria)	66	66	
Safety (% of criteria)	100	100	
Score (% of criteria)	**70**	**60**	

Table 5.5: Comparison of indicators and final assessment

Scenario A is slightly preferable. The assessment indicates that, while in the economic and safety areas scenarios' performance is coincident, significant differences are seen in the area of infrastructure and environment. The significant deployment of nuclear energy foreseen in the B scenario requires noticeable efforts in the infrastructure area. The need for additional capacity and corresponding fuel cycle services (e.g., enrichment services) is certainly challenging. In this scenario highly developed industrial structures are required (logistic, personnel, engineering capabilities, etc.). Proliferation risks and siting licensing difficulties are foreseen in the expansion of enrichment resources.

In both scenarios the depletion of natural uranium resources is a matter of concern. In the B scenario this aspect is counterbalanced by a reduction in GHG emissions. Requirements on financing are not met in both scenarios, however, the impact of this limitation is more pronounced in Scenario B given the higher level of installed capacity.

Overall, the assessment points out some aspects that should be carefully addressed. These issues require to undertake proper actions in due time. The year 2020 has been considered a deadline to arrange favorable conditions for the future development of nuclear energy (NEA, 2012a).

These results reaffirm the need for innovative systems such as fast reactors to overcome the shortage foreseen in uranium resources. The escalation in overnight costs due to safety requirements or longer licensing procedures remains an open issue for the economic competitiveness of nuclear energy.

The assessment has proven to give indications consistent with several issues discussed in the literature. The capability of this set of indicators to catch key features of the proposed nuclear policies has been verified.

In the results presented here the definition of the acceptance limits is an open issue. For the purpose, an ANP model has been developed. It includes all criteria presented in Tab. 5.5. Scenario A and Scenario B are the alternatives under consideration whereas feedbacks and clusters' weights have not been introduced in the model; see Fig. 5.16.

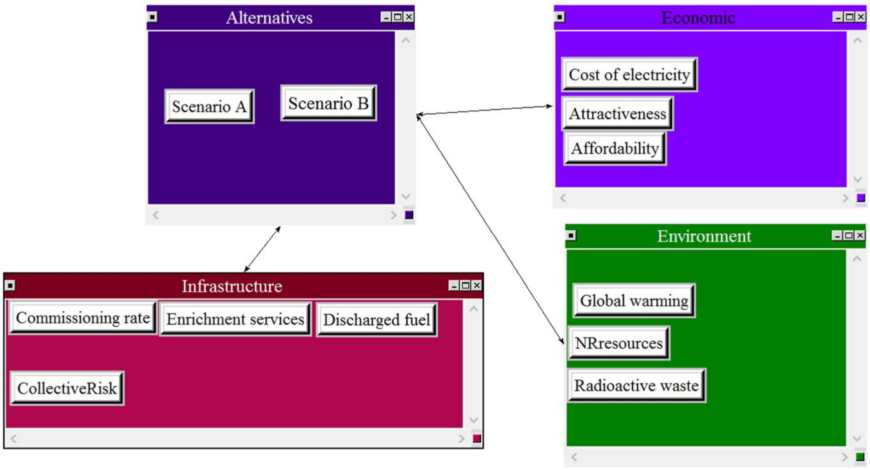


Figure 5.16: ANP model based on the indicators adopted for assessment

The priorities calculated through this model have been compared in Tab. 5.6 with the results presented in Tab. 5.5.

Alternatives	Presented assessment	ANP
Scenario A	53.85	52.63
Scenario B	46.15	47.37

Table 5.6: Comparison of the assessment presented in Tab. 5.5 with an ANP approach

The indication of ANP is in fairly good agreement with the assessment based on an INPRO approach. This verification is encouraging in considering the use of ANP in the concluding part of the assessment.

Besides the fact that the assessor is not required to define the acceptance level needed for the evaluation of each criterion, the adoption of an ANP approach enlarges the role of the assessor and the stakeholders that could assign weights to a specific criterion or groups of criteria. This choice allows decoupling the assessment from the concept of best practice. In addition, the possibility to consider in the assessment the precautionary principle is left open where indicators affected by largest uncertainties could be properly underestimated by means of reduced weights.

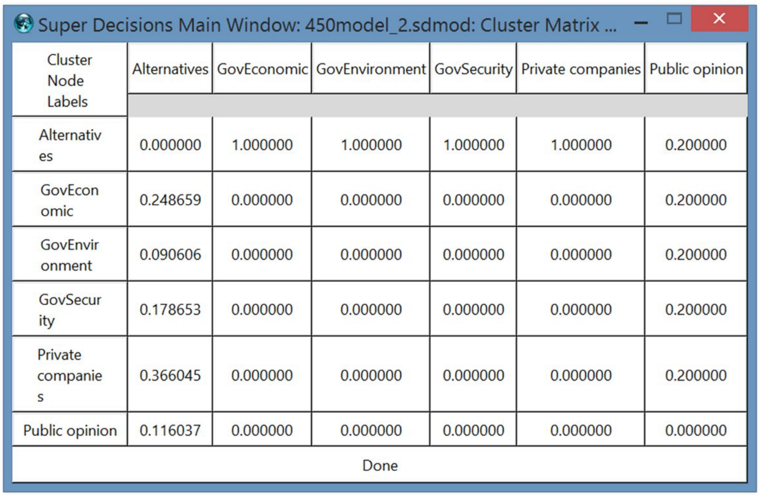
The use of ANP reinforces the consideration of the normative and dynamic principles while avoiding the use of limits internally set and based mostly on norms and standards developed in the course of the historical development of nuclear energy.

5.6 ANP model and stakeholders' viewpoints

The ANP model for the implementation of stakeholders' indications is the initial step of the methodology described in chapter 3. At this stage indicators are agreed and priorities calculated. In this paragraph the results obtained by means of the ANP model previously described are compared with the policies underpinning Scenario A and Scenario B.

Economic performance indicators and parameters used to model each technology have been introduced in the MCDM network presented in paragraph 3.4. For the purpose, input values referring to the base year (2010) have been determined by assuring the consistency of this data with the information presented in chapter 4.

The priorities of clusters are presented in Fig. 5.17. Values are shown in the leftmost column of the cluster matrix. To determine this data pairwise comparisons have been introduced in the model. The dominant role has been assigned to private companies (0.366), the public opinion has a weight of 0.116. Overall, government objectives have the most relevant role in the evaluation of technologies' priorities.



Cluster Node Labels	Alternatives	GovEconomic	GovEnvironment	GovSecurity	Private companies	Public opinion
Alternatives	0.000000	1.000000	1.000000	1.000000	1.000000	0.200000
GovEconomic	0.248659	0.000000	0.000000	0.000000	0.000000	0.200000
GovEnvironment	0.090606	0.000000	0.000000	0.000000	0.000000	0.200000
GovSecurity	0.178653	0.000000	0.000000	0.000000	0.000000	0.200000
Private companies	0.366045	0.000000	0.000000	0.000000	0.000000	0.200000
Public opinion	0.116037	0.000000	0.000000	0.000000	0.000000	0.000000

Figure 5.17: Cluster matrix

The evaluation of each priority is presented in Tab. 5.7. Onshore wind achieves the highest ranking with a value of about 27% followed by solar PV (19%). The priority of nuclear energy is slightly higher than 9%.

Criterion	**Priorities**
1 nuclear	0,09
2 solar PV	0,19
3 onshore wind	0,27
4 coal	0,14
5 natural gas	0,15
6 hydro	0,16

Table 5.7: Alternatives' priorities calculated by means of Super Decisions

The Super Decisions tool allows the user to perform sensitivity analyses on each node of the model. If the node under consideration is an alternative it is possible to modify its priority while the code updates the priority of remaining alternatives in a consistent way with the indications introduced in the model.

Fig. 5.18 shows the results of our model if coal-fired technology has zero priority that is if alternatives are five instead of six and pairwise judgments previously given are not modified.

Scenario 450 is the most ambitious policy presented in (IEA, 2013a). This scenario is broadly consistent with the objective to limit the increase in the global mean surface temperature below 2°C. Renewable energy sources have high priorities in comparison with natural gas and of course coal. The relative rate of electrical capacity addition of the 450 Scenario in the outlook period has been calculated and compared with the outcomes of the model under the hypothesis that the coal-fired technology has zero priority.

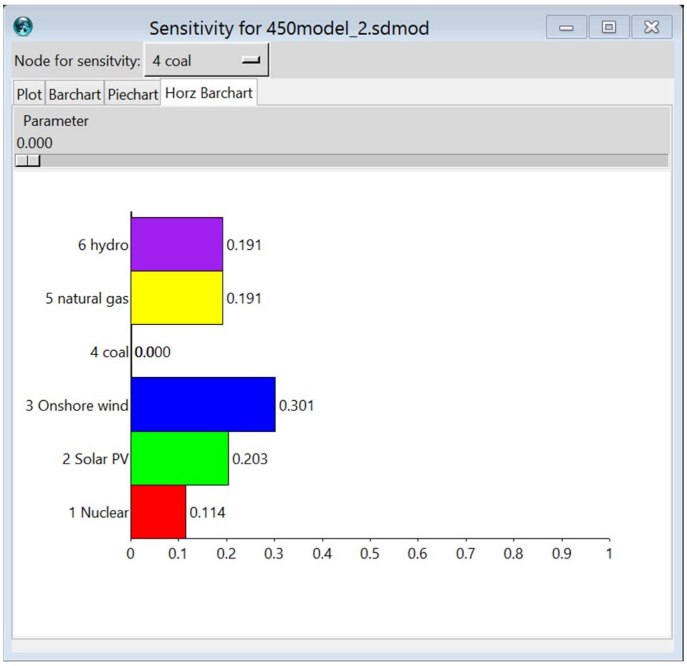


Figure 5.18: Priorities in the case of exclusion of coal-fired from the set of alternatives

The economic parameters have been recalculated under the hypothesis that the overnight cost of nuclear is 8000 USD per kWe and that the attractiveness of gas-fired plants is improved thanks to a higher price paid for electricity (160 mills per kWh). This latter assumption is reasonable under the hypothesis that meeting peak load assures higher revenues.

The introduction of these 2 hypotheses and excluding the coal-fired option as shown in Fig. 5.18 leads to new set of priorities. These results have been compared with the relative rate of electrical capacity addition seen in the 450 scenario. Results are shown in Fig. 5.19. ANP gives indications quite consistent with the investment in electrical capacity accounted in the 450 Scenario. The correlation existing between priorities, stakeholders' viewpoints, and addition of electrical capacity is verified a posteriori in the most ambitious scenario of the IEA (IEA, 2013a).

Scenarios proposed for verification purpose in this chapter have been therefore compared with the outcomes of the model as done in the case of the 450 scenario. In Scenario A and B the relative rate of capacity addition has been calculated in the period 2035-2050.

Priorities have been obtained under following hypotheses:

- nuclear energy has zero priority (Scenario A);
- nuclear energy is an important source of electricity generation resumed through its rate of capacity addition (Scenario B).

Fig. 5.20 and 5.21 present these results as done in Fig. 5.19.

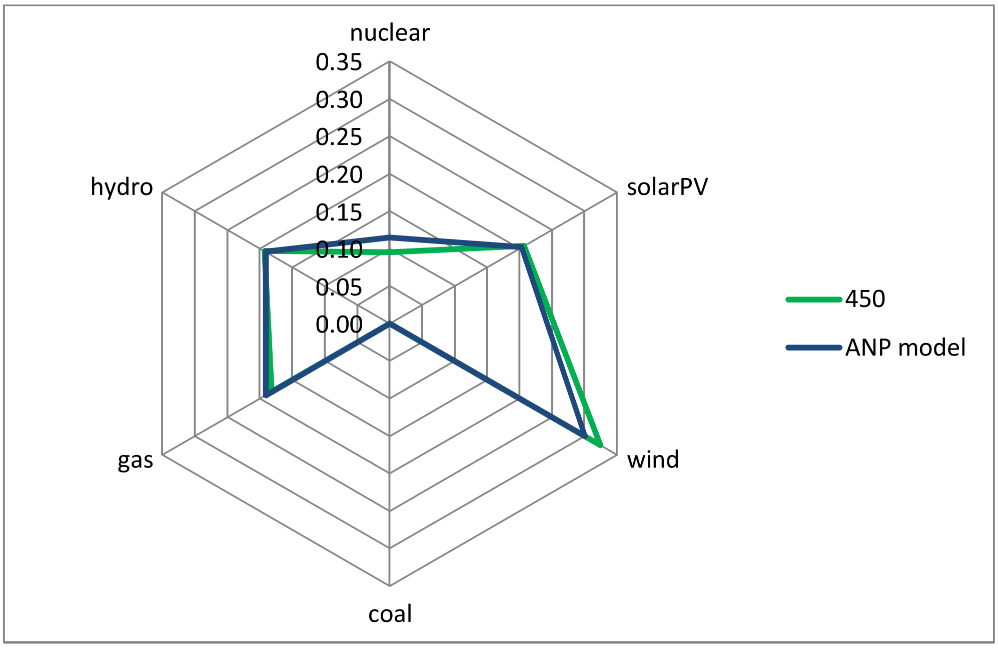


Figure 5.19: ANP model outcomes vs. electrical capacity addition in the 450 scenario

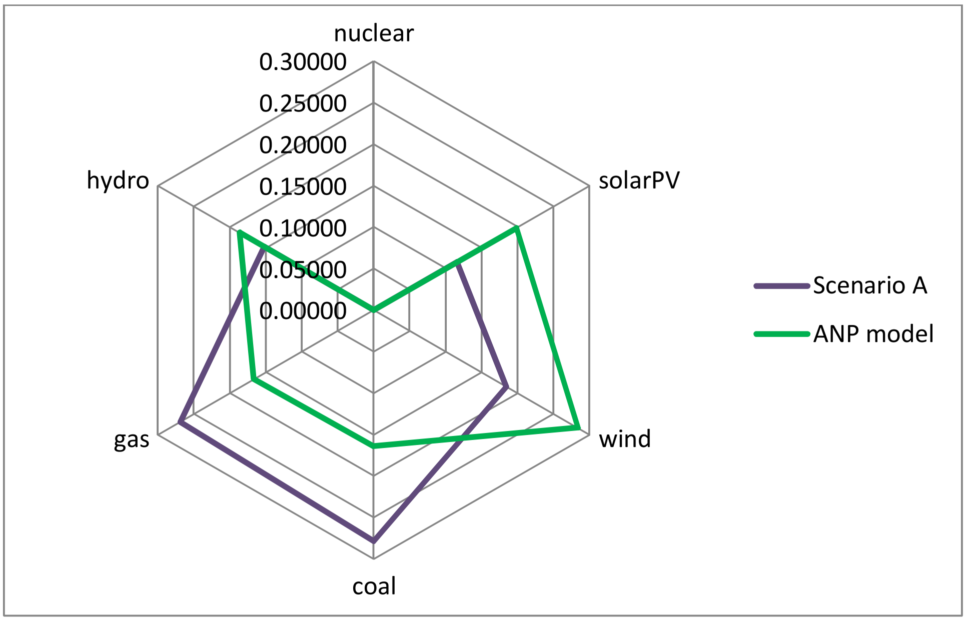


Figure 5.20: ANP model vs. Scenario A (addition of electrical capacity)

The deviations seen in Fig. 5.20 are more pronounced than in Fig. 5.21. The mismatch between stakeholders' viewpoints and adopted energy policies is more relevant in the case of scenario A. Instead, the B scenario is closer to the indications of stakeholders to pursue an effective strategy for the reduction of GHG emissions.

Scenarios proposed for testing purpose confirm the indications given by the analysis of the 450 Scenario and the capability of the model to represent the vision of stakeholders.

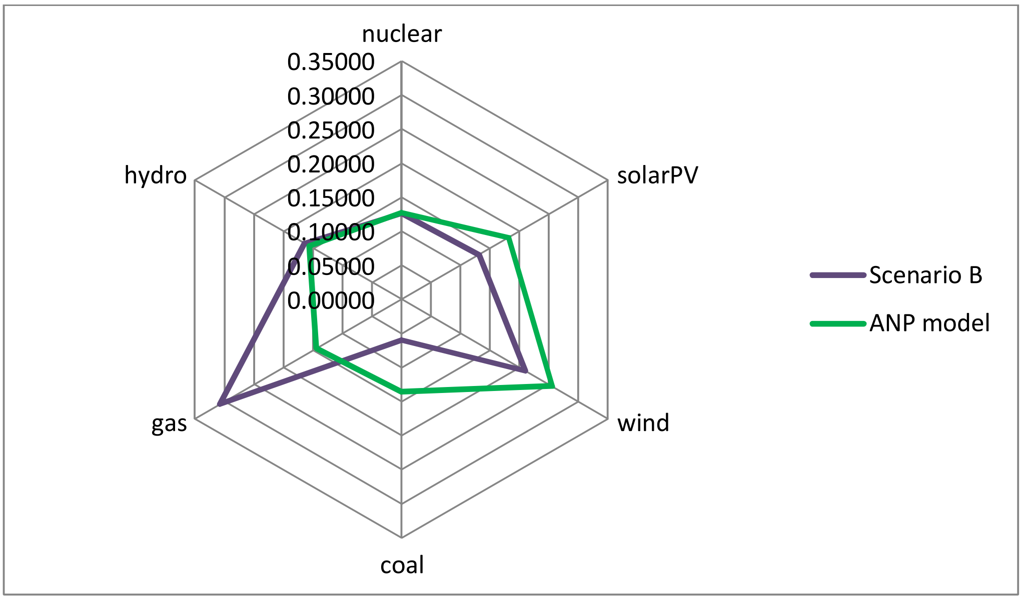


Figure 5.21: ANP model vs. Scenario B (addition of electrical capacity)

This latter verification has given encouraging results to interpret priorities as operative indications for the type of electrical capacity addition. A correlation between priorities and endogenous capacity is therefore suggested for the development of scenarios based on the viewpoints of stakeholders.

The results obtained in this part of the work confirm the satisfactory level achieved in the modeling of technologies with regard to the analysis of economic, technological, and environmental issues of interest. The framework proposed here has confirmed to be capable to implement user-defined scenarios providing results consistent with the analyses presented by the IEA.

More importantly, ANP confirmed to be a reliable and flexible tool for the interpretation and inclusion of pluralistic viewpoints from which scenarios should descend. Operative relationships between priorities and electrical capacity addition and the possibility to introduce constraints in the analysis of the power sector have been confirmed. The use of ANP in the concluding part of the assessment has been verified to be fully consistent with the objectives of the study.

The results of V&V indicate that the layout proposed in this study is capable to achieve an improved compliance with the principles of equity, normativity, and dynamic while maintaining a reasonable agreement with a more traditional approach.

6. APPLICATION OF THE METHODOLOGY

6.1 Introduction

In this chapter the methodology presented and verified in previous chapters is applied. Power scenarios have been developed moving from the viewpoints of stakeholders. Afterwards, the sustainability of nuclear energy has been assessed. A review of energy demand and development of the power sector are presented as prerequisites of the analysis.

6.2 Primary energy demand and the power sector: some historical data

According to (IEA, 2015), in 2013, the primary energy demand reached a level of 13541 Mtoe with an increase by about 122% in comparison with the level recorded in 1973 (6109 Mtoe). In this time frame fossil fuels have met the greatest part of energy demand with a share that in 2013 was still 81.4% despite the fact that a decreasing trend is noted. The energy consumption of OECD countries diminished from a share of 61.3% in 1973 to 39.2% in 2013. Electricity demand increased at a much higher rate than primary energy from a value of 6115 TWh to 23322 TWh (IEA, 2015).

The energy mix of power sector changed markedly as presented in Tab. 6.1. Natural gas and nuclear electricity generation substituted the production based on oil-fired power plants. Besides a sharp increase in renewable energy sources (*Others*), coal remains by far the most important energy source. Overall, the role of fossil energy sources has remained close to the level seen in 1973 with a decrease from 75.1% to 67.4% in 2013. Sharp changes in the energy supplies of power sector seem not realistic.

Electricity generating source	**1973 (%)**	**2013 (%)**
Coal	38.3	41.3
Oil	24.6	4.4
Natural gas	12.2	21.7
Nuclear	3.3	10.6
Hydro	21.0	15.8
Others	0.6	5.7

Table 6.1: Electricity generation mix (2013 vs. 1973) (IEA, 2015)

The significant rate of increase recorded in electricity demand, much more pronounced than in primary energy needs, was mainly due to the rapid and intense economic expansion of developing countries. Here, the industrial development and the improvement of living standards (e.g., number and dimension of households) have been among the most important factors leading to the aforementioned increase. This brief introduction depicts the power sector as a homogeneous entity and this hypothesis has been assumed in the application of the methodology presented in this chapter. However, it is worth reminding that the electricity production is often carried out within national monopolies. Therefore, the electricity mix may vary significantly and could be dominated by different energy sources (e.g., coal, nuclear, hydro) depending on the country under consideration (IEA, 2013b).

The energy sector has well-recognized impacts on the environment. This issue has become a key aspect for a sustainable development and therefore relevant for the definition of future energy policies. Energy-related CO_2 emissions show a trend correlated with the consumption of primary energy. GHG emissions from this sector moved from 15.5 Gt in 1973 to 32.2 Gt in 2013 (IEA, 2015). The contribution of the power sector is significant and increasing. While in 1990 electricity generation accounted for 35.7% of the global CO_2 emissions in 2012 this value has been 41.9% (IEA, 2014). Therefore, electricity generation is relevant not only for the economic development of many areas but also fundamental in regard with concerns on global warming and related climate changes.

6.3 Primary energy demand and the power sector: projections

Reports published regularly by international organizations and private companies have been reviewed to identify development patterns at global level. In this paragraph the indications provided by the IEA, BP, EXXONMobil, and IAEA are discussed (BP, 2016; EXXONMobil, 2016; IAEA, 2015a; IEA, 2014).

Estimations of electricity demand vary from +1.9% per year to +2.5% per year; see Tab. 6.2. The IAEA's estimations are notably higher with values ranging from +2.9% per year up to +3.6% per year (IAEA, 2015a). This information is consistent noting that the IAEA's estimations on primary energy needs are the highest. BP projections assume an optimistic perspective in the conversion efficiency given the high value assumed for the gross domestic product (GDP) (BP, 2016).

More than half of the increase foreseen in primary energy consumption is due to the electricity demand. This quantity will reach by the end of the outlook period shares of primary energy needs in the interval 40.0%-45.0% Emissions will increase at a rate laying in the interval 0.4%-0.9% per year. These values are based on the initial assumptions that each study has employed for the energy and carbon intensity and are generally lower than the estimations of primary energy needs. The growth rate in energy demand by fuel showed to be in good agreement. Deviations of renewables projections are more pronounced but it should be reminded that this category is composed of several technologies (e.g., wind, bioenergy, solar, etc.). These studies agree on the fact that efforts will be undertaken to achieve a decarbonization of the power sector.

Organisation	**EXXONMobil**	**BP**	**IEA**[1]	**IAEA**
Outlook period	2014-2040	2014-2035	2012-2040	2014-2030
Growth rate (% per year)				**Low, High**
GDP	+2.9	+3.5	+2.9	
Primary energy	+0.9	+1.4	+1.1	+2.2, +3.6
Primary energy power sector needs	+1.2	+1.8	+1.5	+3.1, +4.5
Electricity	+1.9	+2.5[2]	+2.0	+2.9, +4.3
CO_2 emissions	+0.4	+0.9	+0.7	
Power sector contribution to primary energy demand increase in the period (%)	50.7	55.6	53.3	50.5, 57.0
Primary energy demand of power sector at the end of the period (%)	40.0	45	42.2	43
Growth rate in energy demand (% per year)				
Oil	-1.2	-1.4	-2.9	
Coal	-0.1	+0.3	+0.6	
Gas	+1.9	+2.1	+1.4	
Nuclear	+2.9	+1.9	+2.3	+1.4. +4.5
Hydro	+1.6	+1.8	+1.9	
Renewables	+3.3[3]	+7.1	+7.1[3]	

[1] New Policies Scenario (NPS)

[2] Estimated from primary energy consumption by assuming power sector efficiency 38% in 2012, 44% in 2035 in agreement with NPS (IEA, 2013a).

[3] excluding Biomass/Waste

Table 6.2: Data and estimations according to reviewed projections

Projections of the power energy mix in terms of primary energy consumption are presented in Tab. 6.3. Some deviations are noted in BP data in the case of hydro and coal. Coal confirms its leading role in power generation.

Electricity generation mix in 2030 (% of primary energy consumption)	**EXXONMobil**	**BP**	**IEA**	**IAEA**
Oil	3.6	2.4	2.4	
Coal	38.3	33.5	40.0	
Gas	25.9	21.6	22.5	
Nuclear	16.6	11.5	15.6	8.6-11.3
Hydro	6.5	16.1	7.0	
Renewables	9.1	15.0	12.5	

Table 6.3: Power energy mix (projections in 2030)

The IAEA's report presents a projection of 71991 TWh by 2050. The corresponding rate of increase is about +3.4% per year over the period 2014-2050. The contribution of nuclear energy accounts for values between 4.2% (low projections) and 10.8% (high projections) (IAEA, 2015a). This data confirms that the development of nuclear energy is prone to several factors that could determine quite different storylines.

6.4 Definition of scenarios

Four scenarios have been defined. Each scenario has been developed by assuming different roles and effectiveness of stakeholders.

Moving from the ANP model presented in chapter 3, stakeholders' roles have been determined through pairwise comparisons of corresponding clusters. Resulting weights are presented in Tab. 6.4. Each scenario has been named to point out hypothetical societal environments where future energy policies could be developed. An additional option has been considered by excluding nuclear energy from the energy mix of the democratic scenario as shown in Fig. 5.18.

The economic parameters have been calculated according to the models presented in chapter 4. Given the long-term view of the analysis, the initial values used for the description of technologies correspond to the data estimated in 2020. Results are presented in Tab. 6.5. An underpinning hypothesis is that the price of fossil fuels remains low and constant across the period.

Cluster	**Democratic scenario**	**Liberalization**	**Security objectives**
Public opinion	0.67	0.08	0.04
Private companies	0.07	0.67	0.04
Gov Economic	0.08	0.09	0.13
Gov Security	0.06	0.07	0.66
Gov Environment	0.12	0.09	0.13

Table 6.4: Clusters' weights presented by scenario

Priorities have been determined by means of ANP. Judgments have been properly refined to assure that the consistency ratio is below 10% as required for the correctness of results. Changes in corresponding pairwise comparisons have been introduced where necessary to maintain the scale typical of ANP. Priorities by scenario are presented in Tab. 6.6. Priorities of the nuclear phase out scenario have been determined according to the indications presented in section 5.6.

In the democratic scenario renewable energy sources achieve high scores. Nuclear energy maintains a significant priority. The phase out of nuclear energy leads to a corresponding increase in the interest towards renewables as well as coal- and natural gas-fired power. In the liberalization scenario the priority of nuclear is confirmed while the attractiveness of fossil fuel generation is more pronounced in comparison with the democratic scenarios.

Economic parameter	Hydro	Nuclear	Gas	Coal	On. wind	Solar PV
ROI (% per year)	13.7	11.2	26.6	19.7	13.7	10.8
	5% discount rate					
LUEC (mills/kWh)	55.5	73.7	59.6	55.3	69.2	81.1
NPV (USD/kWe)	5440	6870	3464	6180	1677	1132
Total invest. (MUSD)	1931.9	12066.3	619.3	1676.8	168.0	199.5
Capital cost (USD/kWe)	3863.7	7541.5	1126.0	2794.6	1680.0	1995.0
	10% discount rate					
LUEC (mills/kWh)	98.2	130.5	72.4	80.6	97.5	119.7
NPV (USD/kWe)	1040.0	-858.7	1738.0	2233.5	496.1	6.3
Total invest. (MUSD)	2126.0	14192.3	681.5	1891.4	176.0	209.0
Capital cost (USD/kWe)	4251.9	8870.2	1239.1	3152.4	1760.0	2090.0

Table 6.5: Economic parameters employed for the determination of priorities

	Democratic	Democratic nuclear phase out	Liberalization	Security
Nuclear	0.07	0.00	0.07	0.13
Solar PV	0.26	0.28	0.21	0.21
Onshore wind	0.27	0.29	0.24	0.22
Coal	0.09	0.11	0.15	0.12
Natural gas	0.13	0.14	0.17	0.11
Hydro	0.17	0.19	0.16	0.22

Table 6.6: Priorities of each technology by scenario

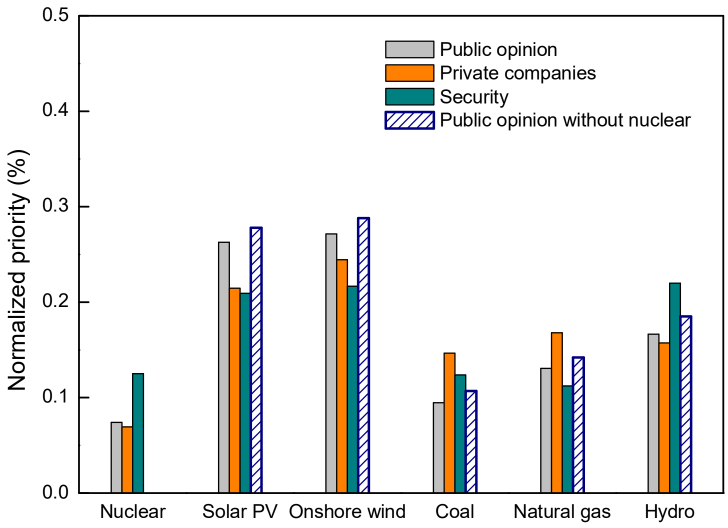


Figure 6.1: Priorities by technology

Economic reasons and the attitude of public opinion are converging on the choice of onshore wind seen as the most preferable option. Nuclear and hydro show a significant performance in the Security scenario. The preference towards renewables is certainly higher in the democratic scenario. The objectives of private companies or the adoption of strategies devoted to improve the security of supplies by governments lead in our calculations to a reduction of renewables' priorities. Economic reasons are mostly driving the interest of private companies towards the generation from fossil fuels.

The indications of ANP are based on the choice of indicators and the information introduced by means of pairwise comparisons. It is worth reminding that these initial assumptions should be properly assessed through interviews, surveys or other means to validate the viewpoint of each stakeholder as pointed out in many references encountered in our review.

6.5 Analysis of the power sector and environmental loading

Four scenarios consistent with the outcomes of ANP have been studied. The outlook period moves from 2013 (base year) up to 2050. Values of generation and electrical capacity adopted in the analysis have been summarized in Tab. 6.7.

	coal	**gas**	**nuclear**	**hydro**	**wind**	**solar PV**
Generation (TWh)	10658.2	5061.9	2472.1	3801.5	575.5	107.2
Capacity (GW)	2285	1450	370	1123	312	109

Table 6.7: Initial conditions assumed in calculations (IEA, 2015)

According to the review presented in section 6.3, calculations have been performed by assuming a growth in electricity demand of +1.9 % per year. Coefficients employed for the estimation of emissions are based on the IPCC Fifth Assessment with climate Feedbacks (IPCC, 2013).

Retirement curves of existing electrical capacity have been developed in agreement with the indications presented in Tab. 4.6.

In calculations the curve of peak load expressed as percentage of total energy moves from 17% during winter days (1095 hours) down to 8% in autumn days (1095 hours). The average load factor is 78% with a reserve margin that in the base year is 70.5%.

The rule used for dispatching is the merit order. Gas-fired plants are in charge of middle and peak load. For the purpose, two types of CCGT plants have been considered. However, the overall constraint imposed by the indication of ANP is respected. These plants differ in their value of maximum availability (85% in peak plants, 60% in middle load plants). Onshore wind and solar PV are employed for base load as well as coal, nuclear and hydro.

New capacity in compliance with the adopted reserve margin is needed to meet the electricity demand and substitute the retirement of existing capacity. To accomplish this requirement the LEAP code adds in the analysis new capacity (endogenous capacity). In the first year of calculations (2014), the planning reserve margin has been reduced to avoid spurious additions of capacity that could bias following results. Afterwards, the reserve margin moves back to its initial value (70.5%).

The addition of endogenous capacity is carried out in agreement with the priorities summarized in Tab. 6.6. As aforementioned, the contribution of natural gas has been shared by two types of plant dedicated to meet the middle and peak load (merit order 2, 3).

The maximum availability of electricity generating plants has been defined to match the capacity factors described in previous sections. The planning reserve margin was ideally maintained at the level assumed in the base year. Under these hypotheses the electricity demand remained partly unmet as shown in Fig. 6.2.

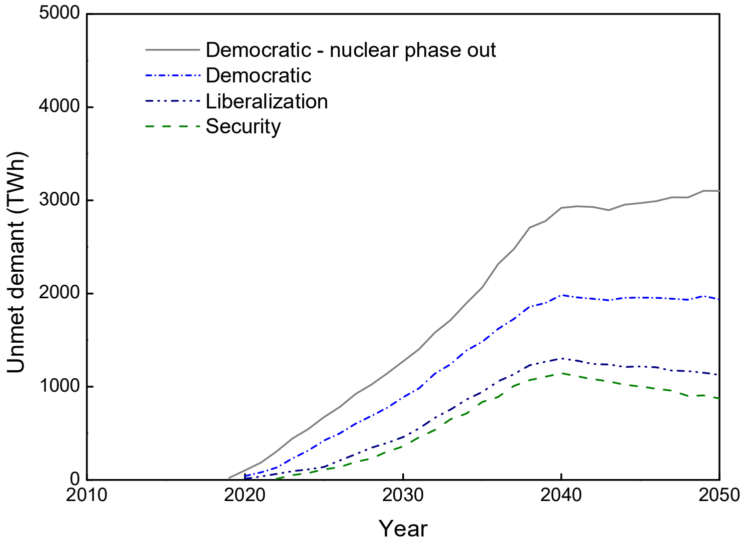


Figure 6.2: Unmet demand by scenario

These indications confirm that the introduction of renewable energy in the power sector requires additional electrical capacity to meet demand at the conditions applied in this analysis. Significant reductions in the capacity factor of conventional plants are foreseen.

The total electrical capacity addition is consistent in all scenarios with rates mostly in the interval 250-450 GWe per year with peaks around 470-550 GWe in 2039. Capacity factors of endogenous plants are resumed in Tab. 6.8. The data is referring to 2040 and show a fairly good agreement with the indications discussed in chapter 4.

	Democratic	**Democratic** nuclear phase out	**Liberalization**	**Security**
Nuclear	88.5	-	88.3	84.2
Solar PV	25.2	26.0	25.1	23.9
Onshore wind	28.0	28.8	27.9	26.6
Hydro	46.6	48.1	46.5	44.3
Coal	60.6	62.5	60.4	57.6
Natural gas (middle/peak)	47.2 / 30.7	54.7 / 39.8	41.7 / 22.1	32.7 / 21.3

Table 6.8 Capacity factors in 2040 (%)

Tab. 6.9 presents the endogenous electrical capacity installed in 2050. The corresponding electricity production is shown in Fig. 6.3 and with more detail reported in Tab. 6.10. It is worth recalling that the exogenous capacity of nuclear and hydro contribute to the production of electricity estimated in 2050.

	Democratic	**Democratic** nuclear phase out	**Liberalization**	**Security**
Nuclear	961.6	-	881.4	1562.7
Solar PV	2496.6	2668.8	1995.2	1904.0
Onshore wind	2578.9	2793.6	2272.8	1949.7
Hydro	2164.4	2423.5	2013.3	2748.3
Coal	1231.0	1401.7	1875.4	1546.1
Natural gas	1475.7	1618.8	1863.3	1200.2

Table 6.9 Endogenous electrical capacity by scenario in 2050 (GWe)

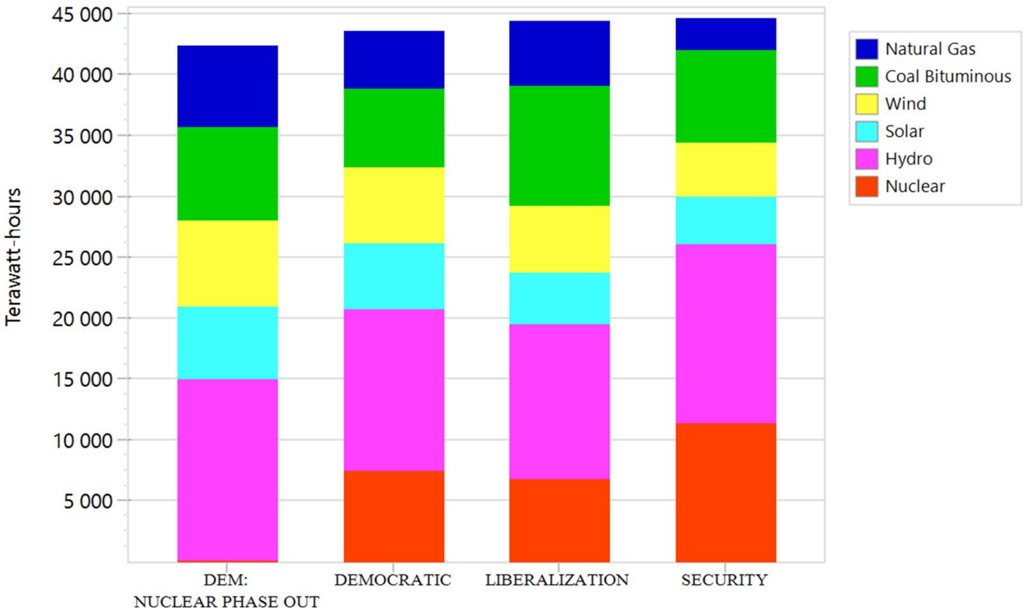


Figure 6.3: Generation by fuel in 2050

Fuels	**Democratic**	**Democratic** nuclear phase out	**Liberalization**	**Security**
Nuclear	7504.3	136.9	6870.8	11401.4
Solar PV	5439.9	6042.8	4336.1	3905.2
Onshore wind	6243.6	7028.2	5488.0	4443.4
Hydro	13265.0	14870.6	12622	14704.2
Coal	6457.4	7640.6	9811.8	7634.2
Natural gas	4653.8	6681.0	5244.2	2537.5
Total	43563.9	42399.9	44373.0	44625.8

Table 6.10 Electricity generation in 2050 (TWh)

Demand for primary energy resources are presented in Tab. 6.11.

Fuel	**Democratic**	**Democratic** nuclear phase out	**Liberalization**	**Security**
Natural Gas	23594.2	29906.5	25450.8	25450.8
Coal	74046.1	86395.9	85939.5	85939.5
Nuclear	41584.8	11137.8	39326.5	39326.5
Total	139225.1	127440.2	150716.8	150716.8

Table 6.11 Primary energy requirement by scenario (Mtoe)

Production costs are reported in Tab. 6.12. The value of discount rate in LEAP calculations is 5%. Results are in reasonable good agreement with the corresponding indications of NEST where prevailing technologies show similar values of LUEC. These results do not take into account the interest during construction.

	Production costs (Billion of USD)	**Production (TWh)**	**Average cost (mills/kWh)**
Nuclear Phse Out	59707.35	1187558.6	50.3
Democratic	59485.2	1207300.3	49.3
Liberalization	60836.3	1222843.9	49.7
Security	64148.8	1226993.6	52.3

Table 6.12 Production costs by scenario averaged in the aoutlook period

The long-term global warming potential due to CO_2-eq emissions at the end of the outlook period is lower than reported in 2013 (13257 Mt) in all scenarios; see Tab. 6.13.

	Democratic	**Democratic** nuclear phase out	**Liberalization**	**Security**
100-year GWP	6257.9	9515.1	9182.3	6510.3

Table 6.13 Global Warming Potential (Million metric tonnes CO_2 equivalent)

This brief review of results confirms that the scenarios developed moving from the viewpoints of stakeholders provide consistent data. Electrical capacity, electricity generation, and capacity factors are consistent with the initial models. Economic and environmental indications showed to be in fairly good agreement with the determination presented in previous chapters.

This step has permitted to account for the effect of the load curve as well as the planned reserve margin. In real applications of the methodology these factors should account for the description of local conditions. This aspect reinforces the capability of the methodology to consider local or geographical peculiarities for a proper analysis of sustainability. The introduction of significant shares of generation from renewables may have an impact on the actual capacity factor of technologies competing to meet base load unless to leave part of demand unmet.

The demand for primary energy should also be taken into account where an assumed intense development of a specific energy source could be unfeasible because of an insufficient level of proven resources. For example, the margins for a potential expansion of hydro are generally assumed to be lower than the indications presented in this assessment. A proper consideration of the use of non-renewable resources is fundamental given the role played by the intergenerational equity issue in the assessment of sustainability.

The analysis of the power sector provides a deeper insight of various aspects of the equity principle and enhances the consideration of the dynamic principle in the assessment.

6.6 Nuclear energy and final assessment

With regard to nuclear, the electrical capacity determined in the analysis of the power sector proved to be realistic and in reasonable good agreement with the indications reported in (IEA, 2014). Fig. 6.4 shows the exogenous and endogenous component of the electrical nuclear capacity by scenario. It is worth recalling that in this analysis, the exogenous capacity stands for generation II nuclear power plants, endogenous capacity is assumed to be constituted of generation III nuclear power plants. A once-through fuel cycle is therefore assumed.

While the development of nuclear energy is not that different in the democratic and liberalization scenario, a relevant rate of increase is seen in the security scenario. Based on these outcomes, the indicators and evaluations parameters adopted for the assessment of nuclear energy have been calculated by means of DESAE. Results are presented in Tab. 6.14.

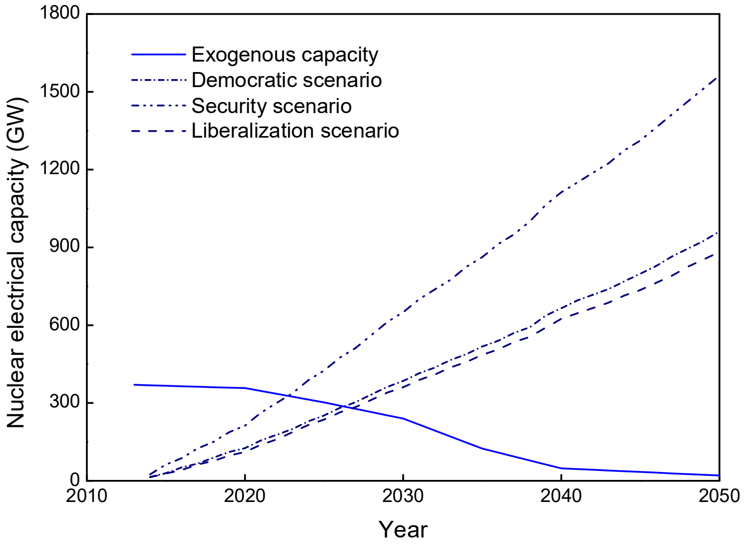


Figure 6.4: Installed nuclear capacity by scenario

As discussed in section 5.5, ANP has been applied to determine which scenario could better fulfil the criteria adopted for the assessment of nuclear energy. Three alternative scenarios have been therefore included in the model and the numerical criteria introduced. Corresponding pairwise comparisons have been checked to assure that the consistency ratio is below 10%. This model is shown in Fig. 6.5.

Evaluation parameters	**Democratic**	**Liberalization**	**Security**
Nuclear Power Production			
EP1.1 (GW/yr)	25.3 (29.6)	23.2 (29.2)	40.1 (50.0)
Nuclear Material Resources			
EP2.1 (TWh/%NRR)	2779 (63.9%)	2794 (60.4%)	2995.6 (91.6%)
Discharged Fuel			
EP3.1 (tonnes/GWa)	17.41	17.75	15.64
EP3.2 (kW/GWa)	34.34	32.39	44.77
Radioactive Waste			
EP4.1 (Sv/GWa)	1.08645E+10	1.1307E+10	8.14364E+09
Fuel Cycle Services			
EP5.1 (% of proven resources)	91	81	175
Safety			
EP6.1 (YOLL/TWh) (presented YOLL times total TWh)	2.11e+06	2.01E+06	2.96E+06
Cost			
EP7.1 (mills/kWh)	73.5	73.5	74.7
Attractiveness			
EP8.1 (% per year)	11.20	11.20	10.96
EP8.2 (USD/kWe)	6929.1	6929.1	6616.5
Affordability			
EP9.1 (MUSD/year)	190798.4	174961.4	302411.6
Climate change mitigation			
EP10.1 (Mtonnes of CO_2-eq)	6257.9	9182.3	6510.3
Average capacity factor (%)	86.8	86.8	83.7
Electricity (GWa)	20266.1	19238	28356.4

Table 6.14 Values of indicators and additional parameters by scenario

The concluding step of the assessment requires the evaluation of scenarios' priorities. These results are resumed in Tab. 6.15. Ideal, normalized and raw priorities are presented. In the first case the most preferable option is assigned the unit value, in the second description priorities are normalized. The raw data is the numeric value in the final supermatrix at the end of iterations.

Results of the assessment indicate that the liberalization scenario is the most sustainable option with a small advantage in comparison with the democratic scenario. The security scenario is the less preferable option, however, it is still worth of attention by policy-makers as proved by its performance not so far from the liberalization and security one.

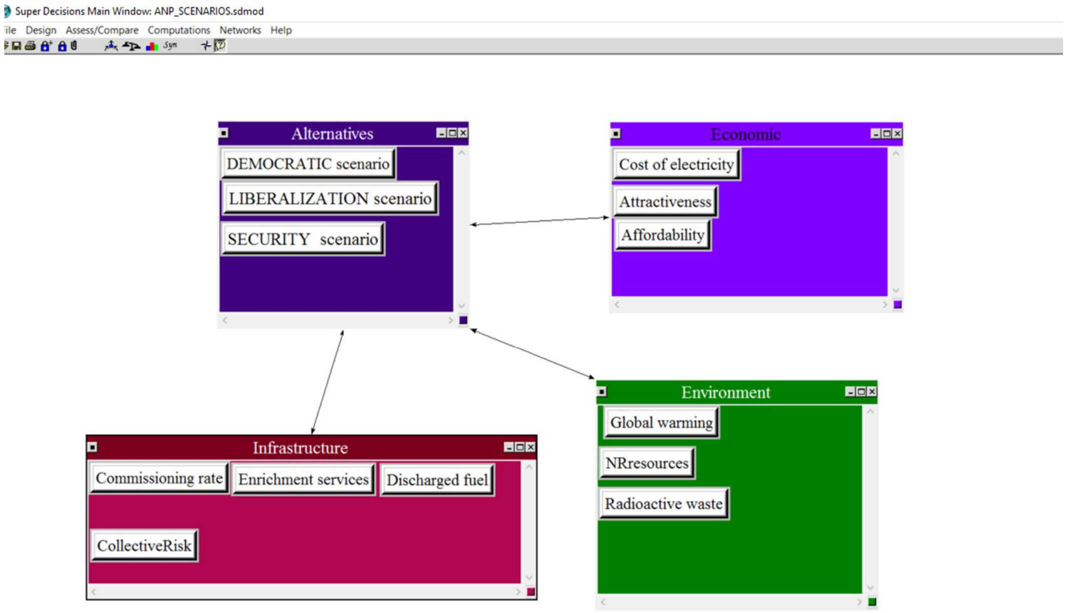


Figure 6.5: ANP model used for assessment

Scenario	**Ideals**	**Normalized**	**Raw**
Democratic	0.984666	0.347561	0.173780
Liberalization	1.000000	0.352973	0.176487
Security	0.848410	0.299466	0.149733

Table 6.15: Scenarios' priorities

The application of the methodology proved to accomplish its objectives through all its steps. Results are consistent and in agreement with the indications found in the literature. The use of ANP appears to make the framework more flexible and suitable for the discussion and integration of different viewpoints.

A better integration of these instances in a methodology consistent with the INPRO approach to sustainability has permitted to develop on a sound technological and economic description of technologies a framework more consistent with the principles considered the real essence of sustainability (equity, normativity, integration). The analysis of the power sector gives the opportunity to the assessor to enlarge the information and the data on specific cases as well as a better consideration of alternative options and patterns of development in compliance with the dynamic principle.

This different approach has also modified the objective of the assessment that from the consideration of the proper conditions and best practice for the deployment of nuclear energy especially for developing countries moves towards a wider consideration of sustainable development. In this view, the decision to not use acceptance limits avoids a too strict link to norms and standards typical of a traditional approach to the assessment of sustainability where only specialists may manage complex issues such as those related to the nuclear technology. In the place of this approach a more ample consideration of global parameters and constraints should be part of the assessment of nuclear scenarios to make decisions fully responsible of the complex matter under discussion.

The framework proved to be capable to structure the complexity of the matter and to catch key aspects of the problem. The procedure takes into consideration many quantities and parameters all relevant for the analysis of the system in a holistic approach mandatory in an assessment of sustainability. The production of manageable data for the analysis of alternatives is an objective of the assessment that these preliminary results confirm to have been achieved.

7. CONCLUSIONS

The concept of sustainable development has been deeply influenced by the publication of the *Our Common Future* report in 1987. Since then the scientific community has continued its efforts to identify principles, indicators, and methodologies that could properly interpret the inherent multi-dimensional essence of this concept and its assessment.

In this view, a series of principles has been identified by researchers. Dynamic, normativity, equity, and integration principles have been judged mandatory for a sustainable development. These principles should also underpin the assessment of sustainable development.

According to the dynamic principle, a sustainable development is a process of change where alternative options are considered. The equity principle considers a fair distribution of benefits and burdens. The integration principle requires to harmonize traditional objectives with environmental and social objectives. The normativity principle considers that norms and rules adopted for a sustainable development are strongly linked to beliefs and values of individuals.

The assessment of sustainability should entail all these elements whose interpretation by researchers is still ongoing. This approach requires methodologies and tools different from a traditional analysis mostly based on analytical evaluations and optimization objectives.

The assessment of nuclear energy sustainability is a challenging task where economic aspects, environmental objectives, and social tensions are all relevant factors for its future development. The IAEA has developed a worldwide acknowledged framework for the assessment of nuclear energy sustainability named INPRO methodology.

The analysis undertaken on the literature, the IAEA's official documents, and the basic principles of the INPRO methodology has given common indications that some aspects relevant for a proper assessment are not taken in due account within the IAEA's approach. Weak aspects on the consideration of equity, normativity, and dynamic principles have been identified and discussed.

The methodology presented in this document offers to the assessor a layout where aspects such as the consideration of stakeholders, the democratic participation in decisions, and the consideration of alternative patterns of development in the power sector are reinforced. These elements are coupled with a tool capable of catching the key requirements of the INPRO methodology.

If on the one hand the proposal intends to overcome some limitations for a more ample and consistent analysis of sustainability, on the other hand the proposed schema pursues a methodologic improvement towards paradigms closer to the indications of the literature. The INPRO methodology adopts an approach mostly based on norms and acceptance limits in agreement with the culture and knowledge developed since the origin of nuclear energy. In our proposal, the use of multi-criteria decision-making methodologies and the consideration of subjective aspects appear to be more consistent with a vision that pursues a better harmonization of the different dimensions of sustainability with a clear distinction from the identification of a best practice technology.

The verification and validation work performed on the proposed schema has given positive indications. The framework has been applied to an assessment where nuclear energy and most relevant competing technologies for electricity generation are considered. Outcomes showed to be consistent in giving positive indications on the correctness of the approach. However, the application to specific or real cases could provide a deeper insight in the methodology with a more detailed validation of the approach. This step is certainly crucial for the assessment of the stakeholders' viewpoints that needs for tailored tools especially in the consideration of non-quantitative or subjective aspects.

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Additional information

Member of the Technical Program Committee (Track 11. Nuclear Energy and Global Environment) of the 2013 International Congress on Advances in Nuclear Power Plants (ICAPP 2013), April 14-18, Jeju Island, Republic of Korea.

PREVIOUS EXPERIENCE

Calabrese R. graduated in Nuclear Engineering at POLIMI in 1992. He is a researcher at the Italian National Agency for New Technologies, Energy and Sustainable Economic Development. He works in the nuclear section at the ENEA Center in Bologna.

Since 2010 he has been involved in the analysis of nuclear energy scenarios within national and international projects. Most relevant papers are listed below.

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