

A framework for the selection of the right nuclear power plant

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(Final version received December 2011)

Civil nuclear reactors are used for the production of electrical energy. In the nuclear industry vendors propose several nuclear reactor designs with a size from 35–45 MWe up to 1600–1700 MWe. The choice of the right design is a multidimensional problem since a utility has to include not only financial factors as levelised cost of electricity (LCOE) and internal rate of return (IRR), but also the so called “external factors” like the required spinning reserve, the impact on local industry and the social acceptability. Therefore it is necessary to balance advantages and disadvantages of each design during the entire life cycle of the plant, usually 40–60 years. In the scientific literature there are several techniques for solving this multidimensional problem. Unfortunately it does not seem possible to apply these methodologies as they are, since the problem is too complex and it is difficult to provide consistent and trustworthy expert judgments. This paper fills the gap, proposing a two-step framework to choosing the best nuclear reactor at the pre-feasibility study phase. The paper shows in detail how to use the methodology, comparing the choice of a small-medium reactor (SMR) with a large reactor (LR), characterised, according to the International Atomic Energy Agency (2006), by an electrical output respectively lower and higher than 700 MWe.

Keywords: non-monetary factors; life cycle evaluation; AHP; multi-attribute evaluation; nuclear power; SMR

1. Introduction

One of the most important elements in the production of electricity is the choice of the most appropriate power plant. This selection takes place in the pre-feasibility study, and it has to include financial and numerical values – net present value (NPV) and capital employed – as well as other non-financial aspects – safety – both of which are intrinsically uncertain. The non-financial aspects become definitely relevant when the consequences of the selection impact many stakeholders. For instance, choosing plant A instead of plant B can promote the development of national industries, increase job positions or reduce some risks. So, even if some of the financial performances of plant B are slightly better than those of plant A, it may be wise to choose plant A. The same considerations apply when the issue is producing electrical power by developing new nuclear power plants (NPPs): different projects have to be evaluated in order to find the most adequate size and design.

In order to assess strengths and weaknesses of small-medium reactors (SMRs), an integrated model for the competitiveness assessment of SMRs (INCAS) has been developed. INCAS compares the choice of investment in SMRs versus large reactors (LRs) providing monetary and non-monetary indicators. Carelli *et al.* (2009) and Boarin and Ricotti (2009) presented economic and financial comparisons of large and of small-medium designs. Locatelli and Mancini (2011) show how to deal with non-monetary factors.

The goal of this paper is to define a framework to integrate contributions of different natures, which is mainly the area of applicability of multi-criteria decision-making (MCDM) methods. The literature proposes many tools for the decision maker, however it is not clear which is the best procedure to be used to select the right NPP design considering different factors that can be quantitative (monetary and non-monetary) or qualitative/strategic. This paper fills the gap in the literature proposing a two-step framework that has been implemented in a case study: the selection of the best NPP technology.

2. External factors

The necessity to consider aspects of a different nature has grown through the years, especially in the evaluation of policies and technologies for electricity generation (Haralambopoulos and Polatidis 2003,

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Pohekar and Ramachandran 2004). For example Mirasgedis and Diakoulaki (1997) consider, during the operations phases, the costs of environmental impact and externalities in determining energy prices. They try to translate the physical impacts of different technologies into monetary terms: for traded goods, impact evaluation is based on the average prices in the worldwide market, while for non-traded goods estimates are based on surveys about the common willingness to pay (WTP) to avoid the impact of externalities. The translation of physical externalities into monetary terms is often complicated and could be a wrong solution when considering aspects of different nature:

- The WTP approach is too subjective and could lead to a less robust ranking of alternatives;
- Some factors affecting investment ratings are characterised by a qualitative nature whose monetary translation would be meaningless, too complicated or too subjective. As Saaty (2008, p.84) states: “To make a decision we need to know the problem, the need and purpose of the decision, their sub-criteria, stakeholders and groups affected and the alternative actions to take [...] but there are many more important factors that we do not know how to measure than there are ones that we have measurements for”.

These factors, which are less controllable by investors and heavily influence operations, will be named “external factors”. We define as external a factor we cannot consider in traditional discounted cash flow (DCF) methods for the evaluation of investments because of its qualitative and subjective nature, but which is able to heavily affect the investment attractiveness. Adler (2000) highlights the importance of such factors. He states that traditional approaches for projects’ strategic evaluation, based only on monetary indicators such as internal rate of return (IRR) or NPV, suffer from too narrow a perspective and the inability to consider potential non-financial benefits, which often characterise strategic investments.

Locatelli and Mancini (2011) list and explain external factors which are differential for the choice between LRs and SMRs. According to this work, three groups of external factors have to be considered in the selection of the right NPP technology:

- **Site-related factors**, which influence the number and the extension of available locations for new NPPs. These include technical siting constraints, the local population’s attitude, spinning reserve management and electric grid vulnerability;
- **Welfare-related factors**, which impact a country’s population’s well being. These include impact on employment, impact on the national industrial system, levelised cost of electricity (LCOE) and time-to-market;
- **Project-life-cycle-related factors**, which impact a project’s robustness looking at its whole life cycle. These include historical and political aspects, incremental design robustness (safety) and risks and competences required for the operations.

SMRs were developed during the 1950s and the 1960s. Then, in order to take advantage of an economy of scale, the design was scaled to 1 GWe and more. But innovative SMRs exploit their small/medium size to develop features giving them benefits in terms of economics, as well as in terms of safety and operational flexibility. It has already been proved that, in a certain scenario, the loss of an economy of scale can be balanced out by an economy of multiples, such as standardisation, learning, cost sharing, modularisation and so on (Ingersoll 2009).

Thanks to the reduction of the financial gap and to SMRs’ flexibility and adaptability, the right choice between LR and SMR increasingly requires the integration of financial and external factors.

3. Literature review

The integration of financial/monetary factors’ and external factors’ performance requires the application of MCDM techniques, which were developed to choose the best alternative based on criteria of different natures.

There are two clusters of MCDM methods (Ribeiro 1996):

- **Multi-objective decision-making (MODM)** methods support decision-making processes on continuous spaces. MODM consists of a set of conflicting goals which cannot be achieved simultaneously and which can be solved with mathematical programming techniques (Ribeiro 1996). Major MODM methods are optimisation techniques, which try to represent problems through continuous functions (Figueira *et al.* 2005). An MODM cluster contains multi-attribute utility theory (MAUT) methods, in which each attribute

evaluation is expressed by a common scale (Dyer and Sarin 1979), which is independent from the specific unit of measurement.

- **Multi-attribute decision-making (MADM)** methods deal with the problem of choosing the best solution among a finite set of alternatives. They provide for the application of discrete mathematics to a finite and preconceived group of alternatives (Ribeiro 1996).

The rigorous mathematical programming of MODM methods is not appropriate to solve the problem of the right NPP design selection, which requires evaluating a finite number of alternatives. MADM methods fit this need well but their cluster is very wide. So, a critical literature review of MADM methods was performed. Table 1 summarises the most common and powerful techniques, their strengths and weaknesses and the references considered.

Saaty's analytic hierarchy process (AHP) is one of the most used methods, because of its ability to fit different problems. It could be also implemented through a fuzzy approach, which permits eliciting expert opinion using linguistic variables. Fuzzy AHP better follows human thinking (Deng 1999) because not every pairwise comparison can be expressed by a precise ratio number; a fuzzy set which takes uncertainties into account fits better (Hsieh *et al.* 2004). The main problem of the fuzzy version is the complex and unreliable process of ranking fuzzy sets resulting from the evaluation of alternatives (Leung and Cao 2000).

Outranking methods are usually employed in the ranking of many alternatives but some of them, like the elimination and choice translating reality (ELECTRE) or the preference ranking organisation for enrichment evaluation (PROMETHEE), have the advantage of being based on a global preference model, expressed by preference and indifference thresholds, which permit expressing different degrees of preference between two alternatives. The main weakness is the high number of threshold values required by the decision maker.

TOPSIS is intuitively appealing and easy to understand (Opricovic and Tzeng 2004). It is based on the assumption that the best alternative should have the shortest Euclidean distance from an ideal positive solution (made up of the best value for each attribute regardless of alternative) and the farthest distance from a negative ideal solution (made up of the worst values). Different than outranking methods, further thresholds or parameters are not required. Each performance can be considered in the model through its specific measurement.

4. The two-step process

The choice of the right MADM technique requires a deep analysis of strengths and weaknesses of each method. Some have a solid and reliable mathematic basis, while others can be implemented in a simpler way (Kiker *et al.* 2005).

In the scientific literature, few comparative evaluations among MADM methods can be considered independent from the specific case study, and this demonstrates the inexistence of a single preferable method. Such comparative evaluations cross many different sectors. In environmental policy decision making, Greening and Bernow (2004) state that an MADM technique must be able to consider every stakeholder's opinion, but the right method is definitely case-specific. In other comparative studies (Karni *et al.* 1990, Zanakis *et al.* 1998), the objective is usually the evaluation of consistency in rankings obtained from different MADM methods. Finally, no study states the supremacy of a specific method but each demonstrates that every MADM process requires two kinds of information:

- (1) The performances of different alternatives on each attribute considered in the decision making process;
- (2) The relative importance of different attributes with regard to the objective of the decision making; importance must be represented through importance weights.

In the selection process different designs are evaluated on financial and external attributes. Financial and external performances and weights are then combined through MADM techniques for the final prioritisation.

So, it is useful to separate MADM methods in two different groups:

- (1) Methods requiring importance weights as inputs from external sources: scoring methods, TOPSIS, ELECTRE and PROMETHEE. These require the combined usage of other techniques providing the weights.
- (2) Methods which calculate importance weights as part of their integration process: AHP and its fuzzy version.

Table 1. General strengths and weaknesses of MADM methods.

	Strengths	Weaknesses	References
AHP	<ul style="list-style-type: none"> – Well-established method. – Very flexible and able to fit many problems. – Effective integration of qualitative and quantitative evaluations of attributes. – Pairwise comparisons approach permits a simple and effective expert elicitation of attributes' weights. – It breakdowns every complex problem in simpler and hierarchical components, simplifying its understanding. – It does not require a specific utility function for each attribute: performances of alternatives on attributes are elicited from experts. – It measures the consistency of expert judgments. 	<ul style="list-style-type: none"> – To translate a complex problem into a hierarchical structure could be difficult and subjective. – Pairwise comparisons require expressing <i>how many times</i> A is more important than B. – Each judgment must be expressed through Saaty's nine-point scale, based on crisp numerical values. – It requires too many judgments from experts if there are many attributes. – Possibility of rank reversal. 	<p>Saaty (1980), Hamalainen (1990), Saaty (1990b), Yoon and Hwang (1995), Bharat and Barin (1996), Korpela and Tuominen (1996), Salo and Hamalainen (1997), Zanakis <i>et al.</i> (1998), Akash <i>et al.</i> (1999), Adler (2000), Al-Harbi (2001), Cheng <i>et al.</i> (2002), Greening and Bernow (2004), Navneet and Kanwal (2004), Agalgaonkar <i>et al.</i> (2005), Figueira <i>et al.</i> (2005), Kiker <i>et al.</i> (2005), Vaidya and Kumar (2006), Shin <i>et al.</i> (2007), Saaty (2008).</p>
Fuzzy AHP	<ul style="list-style-type: none"> – It better represents the uncertainty of judgments than the traditional AHP, thanks to the overlapping between fuzzy variables which represent expert opinions. – Decision maker's cognitive process is simpler: he/she uses linguistic variables to express judgments. – It is the most efficient method for expert elicitations. It is also demonstrated by the many applications available in literature. 	<ul style="list-style-type: none"> – Comparison and ranking of fuzzy sets in the final evaluation are complex and unreliable. – Hierarchical structures with more than three levels are difficult to examine in a complete and comprehensive way. – Measurement of consistency is more complicated with respect to traditional AHP. 	<p>Chang (1996), Ribeiro (1996), Beccali <i>et al.</i> (1998), Cheng <i>et al.</i> (1999), Deng (1999), Zhu <i>et al.</i> (1999), Leung and Cao (2000), Kuo <i>et al.</i> (2002), Kwong and Bai (2002), Fan <i>et al.</i> (2004), Hsieh <i>et al.</i> (2004), Kahraman <i>et al.</i> (2004), Yang and Chen (2004), Chiou <i>et al.</i> (2005), Ozdagoglu and Ozdagoglu (2007), Wang <i>et al.</i> (2008), Kahraman and Cebi (2009).</p>
Scoring method	<ul style="list-style-type: none"> – Easy to understand. 	<ul style="list-style-type: none"> – The need for a unique integration function: the more heterogeneous attributes are, the more difficult it will be to find them. – It does not consider how an attribute can be further separated through multiple levels. 	<p>Dyer and Sarin (1979), Yoon and Hwang (1995), Zanakis <i>et al.</i> (1998), Adler (2000), Figueira <i>et al.</i> (2005).</p>
ELECTRE	<ul style="list-style-type: none"> – Well-established method. – It is based on particular outranking relations, less restrictive than dominance relations. – It provides for a decision matrix normalisation and so every attribute can be expressed in its own unit of measurement. – The outcome is a ranking, so it is easier to understand than AHP indices. 	<ul style="list-style-type: none"> – More useful with many alternatives and few attributes (not the case of selection of the right NPP design). – Usually it identifies a restricted group of preferable solutions, instead of the best one. – It considers only the number of attributes for which alternative A outranks B. It does not consider the real existing gaps in values. 	<p>Yoon and Hwang (1995), Georgopoulos (1997), Beccali <i>et al.</i> (1998), Zanakis <i>et al.</i> (1998), Pohekar and Ramachandran (2004), Figueira <i>et al.</i> (2005), Kiker <i>et al.</i> (2005).</p>

(continued)

Table 1. Continued.

	Strengths	Weaknesses	References
PROMETHEE	<ul style="list-style-type: none"> – Thresholds for preference and indifference indexes permit considering non-linear preferences. – Thresholds permit defining different degrees of preference between two alternatives on each attribute. 	<ul style="list-style-type: none"> – Decision maker must fix two thresholds edging performance on each attribute: their subjective values could seriously affect final outcomes. – More useful with many alternatives and few attributes. – Thresholds are subjective and <i>decision-maker-dependent</i>. The higher number of parameters makes the method more complicated and less standardised 	Babic and Plazibat (1998), Haralambopoulos and Polatidis (2003), Pohekar and Ramachandran (2004), Cavallaro (2005), Figueira <i>et al.</i> (2005), Kiker <i>et al.</i> (2005), Nowack (2005).
TOPSIS	<ul style="list-style-type: none"> – It is intuitive and easy to understand. – It provides for decision matrix normalisation and so every attribute can be expressed in its own unit of measurement. – It considers both similarity to a positive ideal solution and distance from a negative ideal one. – It considers the real existing gap between values of different alternatives, and it does not only count the number of outranked attributes. 	<ul style="list-style-type: none"> – More useful with many alternatives and few attributes. – To consider positive and negative ideal solutions could be meaningless for some applications. 	Hwang and Yoon (1981), Yoon and Hwang (1995), Zanakis <i>et al.</i> (1998), Opricovic and Tzeng (2004), Figueira <i>et al.</i> (2005).

Therefore AHP and fuzzy AHP could be implemented in two different ways:

- To support the whole process, till final prioritisation (Al-Harbi 2001, Yang and Chen 2004).
- To determine only importance weights (Kuo *et al.* 2002, Kwong and Bai 2002).

Finally, the choice is between a one-step and a two-step MADM process. In a one-step process, AHP or fuzzy AHP uses elicitation from experts based on pairwise comparisons to get the prioritisation and final ranking of the projects (Saaty 1980, 1990a, 2008). In a two-step process, AHP or fuzzy AHP can be used to get importance weights through elicitation from experts, stakeholders and decision makers. Then weights will be integrated with the financial and external performances of NPP designs using scoring methods, TOPSIS, ELECTRE or PROMETHEE.

The main implications of this choice are:

- The one-step process is based only on elicitations from expert and it is not able to include numerical ballpark estimates of financial indicators usually available in a pre-feasibility study (which is essential information for the choice that can be wasted).
- Attributes' weights are case-specific and, especially in the pre-feasibility phase, the best way to get them is the elicitation of experts' and decision makers' opinions. Pairwise comparisons of AHP or fuzzy AHP are the simplest and most efficient way to elicit expertise (Hamalainen 1990, Hsieh *et al.* 2004).

Previous considerations show that the two-step MADM process can be the baseline choice for the selection of an industrial plant. It permits including expert elicitations for weights and, on the other hand, considering financial and external factors using a non-AHP method for the final integration.

Now it is necessary to choose the right MADM method for each phase.

AHP and fuzzy AHP are the best methods to obtain the weights – see Table 1 and Table 2. Scoring methods, ELECTRE, PROMETHEE and TOPSIS are available for the final integration (the second phase). Table 2 summarises the strengths and weaknesses of methods considering the specific requirements of each phase and of the specific decision making process for the selection of the best NPP design for a certain country.

According to the critical review in Table 2, we suggest the choice of fuzzy AHP and TOPSIS methods. The fuzzy version of AHP takes into consideration the uncertainty on judgments from experts and, above all, it eliminates the need to express judgments of relative importance in the form of crisp numerical values, as is the case for traditional AHP. Fuzzy AHP is perfect to get the weights of elicitation from expert, as demonstrated by numerous similar applications in literature (Beccali *et al.* 1998, Hsieh *et al.* 2004, Kahraman *et al.* 2004, Chiou *et al.* 2005, Kahraman and Cebi 2009). TOPSIS will be exploited for the final integration because it is really simple and easy to understand – these are the most important characteristics for a tool supporting selection and pre-feasibility phases.

Many parameters required by other methods would make the second step too complicated without ensuring a more accurate evaluation because, in the selection phase, decision makers are still dealing with ballpark estimates. Figure 1 provides an overview of the rationale to select fuzzy AHP and TOPSIS.

Finally, the complete process for the selection of the best NPP design for a certain scenario can be summarised in six points:

- (1) Identification of relevant attributes for evaluation and selection. These depend on market, products, technologies and so on.
- (2) Definition of the measurement and evaluation process of each attribute: quantitative or qualitative, monetary or not and so on. Each choice has to be evaluated in respect to each attribute.
- (3) Definition of an attribute's hierarchical structure as required for fuzzy AHP application.
- (4) Elicitation of expert opinion to obtain the attributes' weights. Each expert has to fill in a questionnaire of pairwise comparisons between attributes or groups of them. Fuzzy AHP permits expressing judgments through linguistic variables: each one is linked to a triangular fuzzy number following the scale in Yang and Chen (2004).
- (5) Aggregation of the pairwise comparison matrices from different decision makers using the geometric mean method presented in Kuo *et al.* (2002). Buckley's method presented by Buckley (1985), Chiou *et al.* (2005) and Kahraman and Cebi (2009) is then the baseline choice to obtain the final importance weights. These are fuzzy sets, so a defuzzification process as in Kahraman and Cebi (2009) is needed to obtain crisp values. The most common is the centroid method presented by Opricovic and Tzeng (2004) and other authors (Kuo *et al.* 2002, Hsieh *et al.* 2004, Chiou *et al.* 2005).
- (6) TOPSIS is applied for the final integration as presented by Hwang and Yoon (1981) and Opricovic and Tzeng (2004).

The intuition of using Fuzzy AHP and TOPSIS for project selection is supported by Mahmoodzadeh *et al.* (2007). Starting from Mahmoodzadeh *et al.* (2007) this paper proposes a dramatic development since:

- Mahmoodzadeh *et al.* (2007) deal only with four financial factors, while this paper shows how to include financial/monetary factors (six, including their variances), non-financial quantitative factors (six factors) and non-financial qualitative factors (six factors).
- Mahmoodzadeh *et al.* (2007) have a single cluster of factors while this paper shows how to cluster factors into four groups and how to deal with more than one group. See Figure 2.
- This paper provides an extensive bibliographic review explaining why, for this class of problem, the fuzzy AHP and TOPSIS are the best approaches. Mahmoodzadeh *et al.* (2007) deal with the mathematical side providing the full set of equations (that are not an original contribution). They do not compare these methods with other methods, like ELECTRE and PROMETHEE, and do not justify their choice for the selection.

5. Selecting the best nuclear power plant technology for newcomers in the nuclear market

The six-point method presented in the previous section is now implemented to deal with the evaluation of LRs and SMRs with respect to a given scenario. Among the other the most interesting could be referred to a country that can be considered a newcomer in the nuclear market, (for example Chile, Bangladesh and Egypt) or without a strong

Table 2. Critical review of MADM methods for selection of the best NPP design.

	Method	Strengths	Weakness
1st step - Weight elicitation	AHP	<ul style="list-style-type: none"> – There are dedicated software which simplify elicitation from experts and final ranking. 	<ul style="list-style-type: none"> – It does not take into account the uncertainty associated with the mapping of human judgment to a number (Yang and Chen 2004). Experts must give <i>crisp numerical</i> judgments of relative importance for each attribute on each other. – Experts must judge <i>how many times</i> one attribute is more important than another.
	Fuzzy AHP	<ul style="list-style-type: none"> – Experts do not have to express <i>how many times</i> an attribute is more important. They express their opinions through simple linguistic judgments. Since they are not dealing with numbers but words it is easier to express their judgments. Later the researchers will transform these judgments in numbers with the fuzzy algebra obtaining more accurate results as discussed in the papers referred to fuzzy AHP quoted in Table 1. – Overlapping of fuzzy judgments well consider uncertainty and vagueness of the subjective perception. 	<ul style="list-style-type: none"> – Mathematic elaboration is more complicated, but only if method is used for the final integration (2nd step). – No dedicated software. – Less experienced method, both in theory and real case application.
2nd step – Final integration	Scoring method	<ul style="list-style-type: none"> – Simple and easy to understand. 	<ul style="list-style-type: none"> – It is difficult to find a unique function able to represent the relationships among performances.
	ELECTRE	<ul style="list-style-type: none"> – Decision makers can customise the process fixing different thresholds for the indices. 	<ul style="list-style-type: none"> – Thresholds strongly affect the final ranking and make it subjective, requiring too much information from the decision maker. – More useful with many alternatives and few attributes.
	PROMETHEE	<ul style="list-style-type: none"> – Decision makers can customise the process fixing different thresholds for the indices. 	<ul style="list-style-type: none"> – It requires the elicitation of a preference and an indifference threshold value for each attribute. The process is more complicated and the higher request for information does not guarantee a better ranking of designs, considering that the decision maker is dealing with ballpark estimates in the selection phase.
	TOPSIS	<ul style="list-style-type: none"> – Simple and easy to understand. – It considers the effective difference between values on each attribute for different NPP designs. – Every performance can be evaluated using its specific unit of measurement. – It does not require more information, threshold values or parameters from a decision maker. The process is simpler and less subjective. 	<ul style="list-style-type: none"> – More useful with many alternatives.

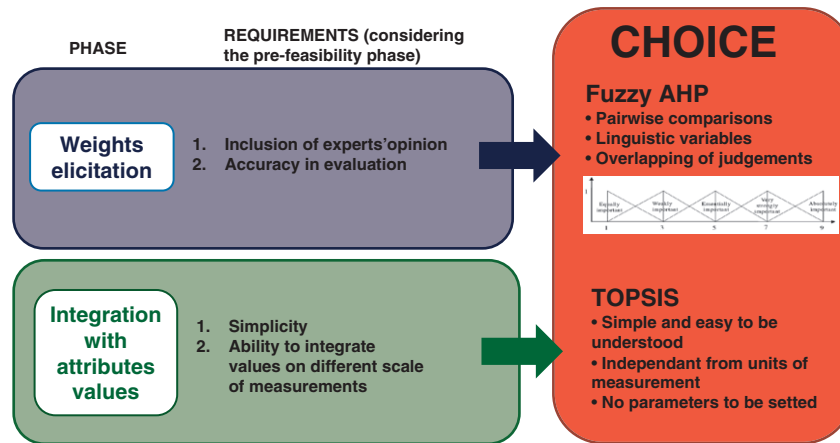


Figure 1. Selection criteria.

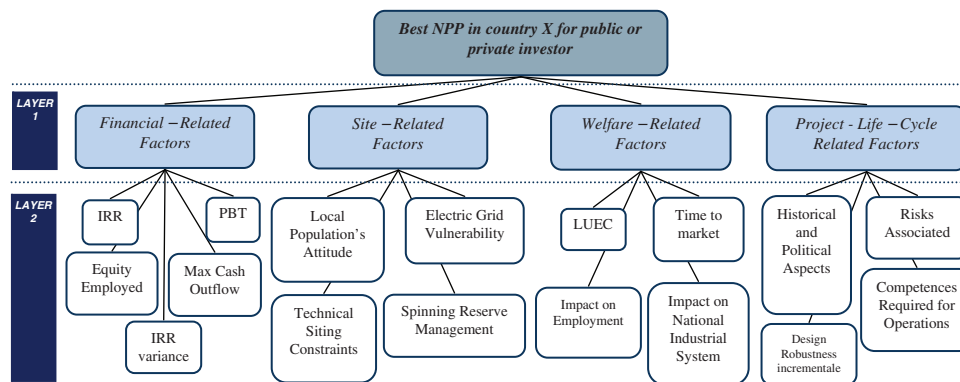


Figure 2. Hierarchical structure for weight elicitation using fuzzy AHP.

national manufacturing nuclear industry (such as Spain, Argentina and Finland). The power to be installed is about 10–15 GWe. As stated in Section 1, this case study is included in the application of the whole INCAS model.

Points 1–2: The first two points are carried out in the development of INCAS: decision makers, experts and literature reviewed indicated 18 relevant attributes evaluating NPP project attractiveness. As presented in Figure 2, six are from traditional DCF methods, others are qualitative and quantitative external factors, already listed in Section 2.

- Among the financial factors, IRR, its variance and payback time have been chosen to consider expected profitability and risk of LR and SMR investment. Equity employed and max cash outflow evaluate the expected impact of self-financing; sequencing NPP unit construction in the right way, investors can capitalise power production from the first installed units, reducing need for debt or equity. This is the so called the “self-financing option”.
- Locatelli and Mancini (2011) developed a specific model to evaluate LRs and SMRs and the performance of each non-DCF attribute (site, welfare and project life cycle related).

The default scenario is composed of 13 GWe, considering six sites available for the installation. The LR scenario is composed of a mix of four 1600 MWe and six 1100 MWe power plants, while in the SMR scenario there are 39 335 MWe power plants. INCAS evaluated the overall performances with respect to each attribute.

INCAS is a mathematical model developed to investigate the attractiveness of an investment in new deliberately SMRs by means of a systematic and comprehensive approach. SMRs are a new product in the nuclear industry since

Table 3. Weights and final integration results for best NPP technology.

Attribute	Class of factors	Weights of class	Weights of attributes in the class	Absolute weights of attributes	Best performance
IRR	Financial related	30.1%	29.7%	8.9%	LR
IRR variance			20.7%	6.2%	Roughly equal
Payback time			20.1%	6.1%	Roughly equal
Equity employed			17.2%	5.2%	LR
Max cash outflow			12.4%	3.7%	SMR
Spinning reserve	Site related	24.9%	7.4%	1.8%	SMR
Grid vulnerability			13.2%	3.3%	SMR
Local population's attitude			56.5%	14.1%	Roughly equal
Technical siting constraints	Welfare related	24.0%	23.0%	5.7%	SMR
Time to market			15.0%	3.6%	SMR
Impact on employment (construction)			5.8%	1.4%	SMR
Impact on employment (operation)			5.8%	1.4%	SMR
Impact on national industrial system			20.5%	4.9%	SMR
Levelised cost of electricity			53.0%	12.7%	LR
Risk associated with the project			Project life cycle related	21.0%	33.0%
Design robustness	22.1%	4.6%			SMR
Historical and political aspect	32.2%	6.8%			LR
Competences required for operations	12.8%	2.7%			SMR
Final index C_{SMR}		0.4623	The best solution has the highest		
Final index C_{LR}		0.5377	value of C: LR's are slightly better		

they are not a scaled version of LR, but a new concept of the NPP. They aim to take advantage of a smaller size to implement new technical solutions and an easier construction. SMRs intend to exploit an economy of multiples¹ rather than an economy of scale. The IRR is one of the most important financial indicators for the investors, in particular when utilities are privately held companies aimed at maximising the return for the investors. According to Boarin and Ricotti (2009) LR's are more profitable because of a higher IRR. SMRs are attractive in scenarios with limited financial resources, where the utilities can add modules exploiting self-financing options. The maximum financial exposition can be reduced so even if the capital cost is slightly higher for the SMRs, thanks to the self-financing option, the capital employed (debt + equity) is similar. This is due to the compensation of the economy of scale by the economy of multiples. Therefore, instead of a monolith LR providing a large amount of power at once, a series of SMRs allows a gradual connection to the electricity grid. With this approach, the first units can finance the construction of the following units, reducing and diluting the upfront investment. For what it concerns the capital employed this is an advantage since less financial resources are required. On the opposite for what it concerns the financial gain it is a disadvantage. In fact the shareholders receive a lower remuneration of their equity since the inbound cash flows are gathered later. SMRs, due to the lower up-front investment, can be a reasonable choice in the case of limited resources since they can wait and see multiple strategies. The contemporaneous construction of a large number of SMRs is not a reasonable choice because they cannot reap the advantages from learning and self-financing, that is to say the economy of multiples.

According to Locatelli and Mancini (2011), SMRs perform better, or at least as well as, LR's in all the external factors except historical and political aspects. However it is important to point out that the not in my backyard (NIMBY) syndrome limits the possibility of spreading SMRs to different sites and so of fully exploiting the advantages in grid stability and site availability. However even if many SMRs are grouped in the same site, they still have many advantages through all their life cycle. During the planning and construction phases, more sites can be exploited, the time to market is shorter and there are fewer risks associated with the construction. In the operation phase, SMRs provide more job positions and require smaller spinning reserves.

Point 3: The hierarchical structure for the implementation of fuzzy AHP is presented in Figure 2. Clustering the factors into groups has two main advantages:

- (1) Reducing the number of pairwise comparisons, and
- (2) Allowing an easier judgment since the factors in the same group are comparable.

Point 4: Expert opinions are obtained through a questionnaire designed for fuzzy AHP, following the scheme presented by Ozdagoglu and Ozdagoglu (2007). The questionnaire contains 34 questions, with each one relating to a pairwise comparison resulting from the previous hierarchical structure, and judgments of relative importance are expressed through linguistic variables from the scale introduced by Yang and Chen (2004).

The main reference in designing the experimental design has been Forza (2002). Lahdelma *et al.* (2000) has been the reference to design the survey related to MADM. In particular Lahdelma *et al.* (2000) shows valuable clues. In particular it shows the way to identify the most relevant stakeholders and to provide them a questionnaire with elements that can be easily understood. Ninety-four questionnaires were emailed to academics and managers with a good knowledge of this topic. If after two weeks there was not any answer another email was sent.

At the end of this second run, 22 experts had filled out the questionnaire. The sample includes eight academics, seven managers from utilities and seven managers from main contractors building power plants all around the world.

Points 5–6: Table 3 presents the defuzzified weights obtained from the application of geometric mean and Buckley's methods. It also shows the best performing solution on each attribute and final index (relative Euclidean closeness to ideal solution) for LRs and SMRs. The main goal of the table is to highlight which attributes promote LR choice in the default scenario, and which ones promote SMRs. The two-step process shows that the best NPP in the default scenario is the LR.

6. Discussion

The goal of this research has been to develop and implement a method to integrate the results from INCAS about financial/monetary factors and external factors related to the question of LRs versus SMRs.

First of all, expert opinions confirm that external factors and related classes are approximately as important as financial factors. Therefore, just traditional DCF methods would not be sufficient to guarantee the right choice between LRs and SMRs. In fact, the most important aspect is the local population's attitude (weighing 14.1% of the decision), which is an external factor. Even if it is one main topic in the nuclear debate, as expert elicitations underlined, population attitude towards LRs and SMRs is the same, because different designs and sizes are not perceived as more or less intrusive or risky. So, the roughly equal performance of SMRs and LRs makes local population's attitudes not differential. If the investors are able to communicate the higher safety and design robustness of SMRs, this factor could become differential to promote the SMR choice. However where NIMBY syndrome is strong, to find four different sites for SMRs is more difficult than a single LR site, since the solution to local opposition requires great effort in terms of diseconomy of hassle (Ingersoll 2009), money and risk augmentation. In this case, public acceptance is differential and promotes few large power sites. As a consequence, considering four SMRs in the same site makes public acceptance not differential, even in the case of strong NIMBY syndrome.

According to Table 2, LRs seem to perform better from a financial point of view, even if SMRs contribute to reducing financial risk thanks to their lower maximum outflow in the first phase of the project. On the other hand, 10 out of 12 external factors promote SMR choice in the default scenario. For example:

- During the planning and construction phases, more sites can be exploited, the time to market is shorter, there are less risks associated with the construction and there is a higher benefit for national industries. Due to their smaller dimension, SMRs have the potential to develop a wider supply chain with a higher number of suppliers inside national burdens. Investments to become an SMR supplier are more competitive.
- In the operational phase, SMRs provide more job positions and do not require additional costs in terms of spinning reserves. Fractioning the capacity if, in one hand increases the cost, on the other hand increases the job position and create a more flexible system.

Even if more factors support the SMR choice the two most, IRR and LCOE (weighing almost 20% of the decision), are favourable to LR. Summing up LRs can be put up as a best choice thanks to:

- Higher internal rate of return and lower need for equity (financial); and
- Lower levelised cost of electricity.

It is important to point out that the difference between the score of the two technologies is really slight, and it is therefore necessary to thoroughly investigate performances of attributes.

Sensitivity analyses show that the overall electric power to be installed is most important factor since it influences all the financial factors. Decreasing the power from 13 to 7 GWe, LRs perform as SMRs. Moreover the sensitivity analysis shows that there are several scenarios where SMRs can be a reasonable choice compared to LRs.

- SMRs are competitive with LRs when the power required is 3 GWe or less because the economy of scale is compensated by the economy of multiples.
- In the case of constrained financial resources, the self-financing option and the reduced maximum required upfront investment required are strategic factors for relatively small utilities with limited budgets.
- Where the environment represents a challenge in terms of water availability, earthquakes and so on, safety constrain become even more important.
- SMRs can represent the ideal solution for newcomers without experience in building and operating nuclear reactors. To build and operate an SMR is easier than building and operating an LR (Locatelli and Mancini 2011).

7. Conclusions

Nowadays a significant interest in SMRs is growing in several countries, including those economically and infrastructurally developed. Even the USA is interested in SMRs as recently confirmed by secretary of energy Dr Steven Chu (Chu 2010).

In SMRs, the reduced size is exploited from the design phase to reach valuable benefits in safety, operational flexibility and economics. A rough evaluation based only on the economy of scale could label these reactors as economically unattractive. This approach is incomplete and misleading since the reduction in size paves the way for many advantages such as new technical solutions, cost sharing, faster learning and additional strategic opportunities. All these aspects have been carefully analysed and evaluated. Indeed, the main goals of these research activities have been achieved through the development of an integrated model called INCAS, able to support a systematic and comprehensive evaluation of SMRs, merging economic and strategic objectives. INCAS performs an investment project simulation and assessment of SMR and LR deployment scenarios, returning economic and financial performance indexes (for example, IRR, LCOE, total equity employed and so on) along with external factors (such as design robustness and required spinning reserve). This is a great improvement since traditional DCF methods for the evaluation of investments are not able to consider external factors due to their qualitative and subjective nature. However such factors dramatically influence the construction and operations of each industrial plant. This holistic evaluation has shown that there is not a clear preference toward LRs or SMRs, as some indicators (IRR and LCOE) are better met by LRs, while others (design robustness and spinning reserves) are better met by SMRs. Therefore it is necessary to integrate all factors in a synthetic rank of the alternatives.

Under this perspective, the two-step process presented in this paper is a valuable tool to support the decision-making process in selecting the plants given a certain scenario:

- In the first phase, fuzzy AHP will be used to obtain the importance weights of factors and allows for considering expert opinions in the simplest and most efficient way;
- Resulting weights will be used for the integration of LRs' and SMRs' performances for financial and external factors, through the TOPSIS method, a simple and understandable MADM technique. The final outcome is a unique, numerical and crisp index, which permits the ranking of alternatives. TOPIS integrates the expert judgments with the INCAS values for each single factor.

In conclusion, with respect to traditional AHP, which considers only the judgments of experts, this approach is able to include numerical performances of each attribute, usually evaluated through specific models. It provides the best choice among a finite number of alternatives and, if results show a clear preference toward a certain project, it can be considered a robust solution, otherwise it would be wise to better investigate the most relevant attributes.

Note

1. Economy of multiples refers to the economic advantages in deploying many identical units. If \$100 is the cost of a single unit, the deployment for n identical units is less than $\$100 \times n$ because of the cost savings from industrial learning, standardisation and mass production, cost sharing of non-recursive costs (for example, in the engineering and design), sharing of site-fixed and semi-fixed costs and so on.

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