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IMPACT OF THE EXTERNAL FACTORS IN THE NUCLEAR FIELD: A COMPARISON BETWEEN SMALL MEDIUM REACTORS VS. LARGE REACTORS

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ABSTRACT

Several improvements have been made in the nuclear energy sector during the last decade leading to new design for advanced nuclear power plants.
Literature presents several studies about the economics of these new Power Plants, however the economic analysis of these plants usually considers only the classical accounts related to Construction, Operation & Maintenance, Fuel and Decommissioning. Beside these accounts there are many factors, from now on named External Factors (e.g. social acceptability, enhanced safety, emergency planning zone reduction, etc.) able to heavily determine the profitability of the investment.
This paper presents the differential impact of these External Factors on nuclear technology with different sizes. According to the classification currently in use in the IAEA, small reactors are those with electric generation power lower than 300 MW, while medium sized reactors are those with electric power between 300 and 700 MW [1]. We define "Small Medium Reactors" (SMR) reactors with an electrical output smaller than 700 MW (usually 335 MWe) and as "Large reactors", (LR) reactors with an equivalent electric power greater than 700 MW. (usually 1340 MWe)
Starting from the international literature point of view, the paper provides a list of external factors distinguished in economically quantifiable or not. Two different approaches have been used for their assessment: a monetary ranking and a strategic one. Then, using a Quality Function Deployment approach, a multi-attribute model is introduced to obtain a weight for every external factor, dividing their impacts into three sustainability dimensions (economic, environmental and social). The results show that the new SMR perform better than LR thanks to the smaller size which allows an enhancement of the safety level (which affects the public opinion) and a greater flexibility in the market

1 Introduction

1.1 Small-Medium Reactors competitiveness

The fourth generation of Nuclear Power Plants (NPP) will give a great contribution to reach goals as pointed out in [2]. In particular, the SMR seems to be a good option (maybe the only one) for developing countries with insufficient infrastructures, small electricity grids and limited investment capability. Smaller reactors may also offer the flexibility of power generation and applications required by the market deregulation in the industrialized countries: SMR are interesting for both near term (e.g. oil sand mining, seawater desalination) and advanced future non electrical applications (e.g. usage of process heat, hydrogen production). Finally, SMR embed new technologies, such as passive systems, that are not included in a LR.

1.2 Polimi Open Model and research questions

The interest in the economic assessment of SMR is one of the most important topic for the IAEA [3]. A research group from "Politecnico di Milano" is developling a model (Polimi

Open model) aimed to assess the suitability of SMR respect to LR (both III+). In the base scenario a certain number of MWe must be installed, a generic GEN III/III+ reactor[a] of 1340 MWe or four passive SMR of 335 MWe are the default choices, even if any size can be considered. The International Reactor Innovative and Secure (IRIS), an integral, modular, 335MWe PWR [4] is used as the example of SMR.
The overall model "Polimi Open Model" (Figure 1) is composed by two main modules. The "investment model" constituted by the submodules of "generation cost" (1), "revenue" (2) and "financial cost" (3), These models carry out the investment assessment by considering cost, revenue and financial implications. The model aims to overcome the axiom of "bigger is better" due to the economies of scale, by developing the ideas from the 1991 paper of Shepherd and Hayns, "SIR reducing size can reduce costs" [5]. Obviously if "economies of scale" is the unique driver for the cost estimation SMR are not competitive respect to LR. However many recent references [6-8] point out as this is true as long as the comparison considers the specific cost [$/kWe] of 1 LR respect 1 SMR. On the other hand, when the comparison is carried out considering the same power installed in the site (1340 MWe equivalent to 1 LR or 4 SMR) the result changes. In this case there are other key factors able to reduce the gap between the two classes of reactors. Considering these factors (site sharing, learning, construction timing, fuel cycle length extension, different technology solutions) the specific Capital Cost [$/MWe] of an SMR is only few percents greater than a Large Reactor, while the Operation and Maintenance costs [$/MWh] are about 20% greater. The result change if the comparison is 2 LR vs. 8 SMR since also the second LR reaps advantages from the site sharing.

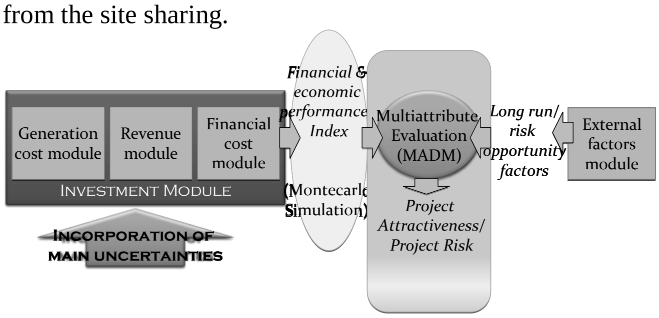

Figure 1 "Open Model" overall conceptual scheme.

The last module of the "Polimi Open Model" is the "external factors module" (4) which is the object of this paper.
An "external factor" is a factor usually not directly considered within the investment evaluation, because is not directly controllable from the investor and it results hardly accounted. However it strongly influences the life cycle and the feasibility of the project itself. Examples of external factors are: security of fuel supply, public acceptance, environmental aspects etc.
To perform the analysis, the module is developed into two phass:

- the first phase assesses individually the external factors and their differential impact on alternative reactor size: LR vs. SMR. At the end it provides a "performance scoring" for each factor and each configuration (**pre-requisite**);
- the second phase integrates the factors and ranks the configuration using a multi-attribute evaluation (**integration**).

The main research questions related to the external factors are:

1. considering an investment in SMR or LR which is the most attractive?
2. which are the strengths and the weakness of the SMR?

This paper provides the general methodology as well as the specific algorithms to quantify these research questions. At the end all the results are integrated in a single chart providing a final evaluation.

2 External Factors Model - Methodological approach

A comprehensive literature about external factors does not exist, but a number of different studies (quoted in the following specific paragraphs) deal with some of them (especially those related to the environmental impact). Therefore the international literature has been used to obtain needed information while for factors without a strong literature background some new indicators have been developed. From this perspective each relative quantification is a new result as well as some of the algorithms used to quantify the absolute values.
The evaluation process for each single factor is summarized in these steps:

1. Factor definition;
2. Identification of phenomenon boundaries;
3. Phenomenon observation with the bibliographical analysis;
4. Absolute Factor quantification;
5. Impact on alternatives;
6. Relative impact quantification based on comparison between alternatives;
7. Performance scoring assignment on the basis of the relative impact (Table 1).

Performance Scoring correspondence matrix		
Relative Impact (*RI*)	**Impact Judgment**	**Performance Scoring**
$RI = 0$	*Non existent*	10
$0 < RI \leq 0{,}4$	*Much Lower*	9
$0{,}4 < RI \leq 0{,}8$	*Lower*	7
$0{,}8 < RI \leq 1{,}2$	*Appr. Equal*	5
$1{,}2 < RI \leq 1{,}6$	*Higher*	3
$RI > 1{,}6$	*Much Higher*	1

Table 1 Relative Impact

This is the scale that has been used for the comparative evaluation and the performance score assignment for each factor in Chapter 4. It's important to highlight that this is a

[a] For the LR the model can assume both a generation III and III+ design, whereas the SMR is always a modular GENIII+ reactors.

"relative" scale where the SMR has a value always equal to 5 and the LR the relative value, so impact judgment are expressed as a relative adjective.
It is then necessary the integration of quantified factors to obtain an overall evaluation of SMR respect to LR. The Quality Function Deployment (QFD [9, 10]), a multi attribute evaluation model, has been chosen as the reference to develop an External Factors-impact Integration Model composed by the following phases: prioritization and selection. Considering four scenarios (the base one and economy, environment, socially-centred scenarios, [11], an overall model it has been obtained as shown in [12].

3 External factors Nuke vs. other technologies

In order to understand how the innovative SMR could be a suitable choice in certain markets it is important to highlight the strengths and weaknesses of actual large reactors respect to the other technologies (coal, natural gas, hydroelectric). The external factors having a potential differential impact for nuclear energy respect to other electricity production technologies are summarized in Table 2.

Factor	Type of quantification
Risk of Severe accidents	Monetary
EPZ preparation	Monetary
Security of fuel supply	Monetary
Volatility of fuel price	Monetary
Environmental aspects	Strategic
Public acceptance	Strategic
Co-generation option	Not yet quantified
Sitting constraints	Not yet quantified

Table 2 External factors relevant for nuclear energy.

Risk of severe accidents is always the most critical external factor [12] typically followed by environment concerns and public acceptability (Figure 2). Safety and social acceptance are strongly correlated and deal with the social aspects of the energy production. Therefore, beside the usual costs accounted in a classical life cycle analysis, factors related to the population account for the most.

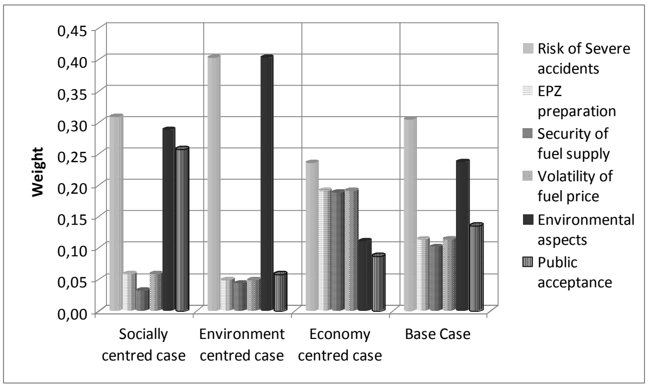

Figure 2 Nuclear vs. other technologies. Factors´ weights according to the different scenarios [12].

The social acceptance of the nuclear technology is a contentious argument. For instance a recent research from the European Union points out as the nuclear technology is the less attractive way to produce electrical energy for Europeans, whereas the solar technology is the most attractive [13]. On the opposite in the USA the majority of the populations accept the construction of new NPP. There are not technological reasons for the irrational attitude of Europeans since any European reactor never had a severe accident. Mostly of these fears come from the Chernobyl accident. The section 4.6 focuses on social acceptance.
These considerations are consistent with the final results coming from the QFD approach [12]. Figure 5 shows as the hydroelectricity plants are always the most suitable choice since these plants do not produce pollution[b], and are well accepted by the population. This result was expected, but in the majority of OECD[c] countries the sites suitable for new large hydroelectric plants with a low environmental impact are negligible.
When all the factors are included in the analysis the nuclear technology achieves the second or third position (with coal) because of the lower performances in public acceptability and in a certain measure to the perceived risk of severe accidents.
It is important to consider that some of nuclear data considered in the analysis are related to the GEN II reactors (all the reactor in operation UE and USA are GEN II), therefore hopefully in the future, these two main weaknesses will be overcome. Consequently in the next chapter will deal with the new GENIII+ reactor focusing on the different behavior of LR and SMR.

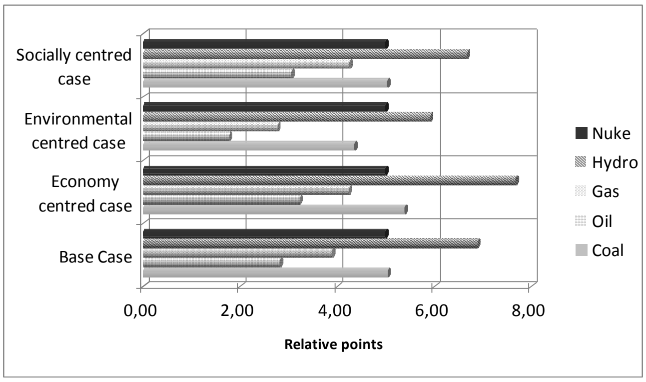

Figure 3 Nuclear vs. other technologies. Results in the different scenarios. [12]

4 External factors identification: Small-Medium Reactors vs. Large Reactors

Nowadays there is a strong background in the literature about the physical characteristics of innovative and evolutionary SMR [14, 15, 3, 16]. Other papers focus more on potential market for the SMR from different point of view as, for example, electric grid characteristics [17-19].

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[b] The externalities of each power plant is a function of many factors (principally technological, but also sitting, waste management ecc…). [39] summarizes the average externalities of the most important power plants. The results show that Nuclear and Hydroelectric plants have externalities lower of orders of magnitude respect to oil, gas and coal. Hydroelectric plants have, on average, an externality even lower than nuclear since do not produce toxic waste.
[c] Organisation for Economic Cooperation and Development.

The most important related to IRIS, the SMR used as example, are widely discussed in [20].
From the international literature about the differential characteristics of the SMR with respect to LR, several external factors have been identified and summarized in Table 3. In the next paragraphs each factor is analyzed and quantified.

Factor	Type of quantification
Security improvement	Strategic
Demand variation	Monetary
Licensing time	Monetary
Electric grid characteristics/Market dimension	Strategic
Equivalent power availability	Monetary
Public acceptance	Strategic
Co-generation option	Not yet quantified
Sitting constraints	Not yet quantified

Table 3 External factors relevant for nuclear reactor size.

4.1 Security improvement

The concept of security has been developed through the four generations of NPP. In the newest generation (III+ and IV), passive safety systems have been introduced [15], therefore the probability of severe accidents has been drastically reduced. However the SMR should be even safer, for instance the IRIS design provides for multiple levels of defense for accident mitigation (Defense In Depth - DID), resulting in extremely low core damage probabilities [4]. In addition to the traditional DID levels (barriers, redundancy, diversity, etc.) IRIS introduces a very basic level of DID, i.e., elimination by design of accident initiators or reduction of their consequences/probability. Table 4 provides an overview of how IRIS deals with Class IV design basis events.

Class IV design basis events	Results of IRIS safety-by-design
Large break LOCA	Eliminated by design
Steam generator tube rupture	Reduced consequences, simplified mitigation
Steam system piping failure	Reduced probability, reduced (limited containment effect, limited cooldown) or eliminated (no potential for return to critical power) consequences
Feedwater system pipe break	Reduced probability, reduced consequences (no high pressure relief from reactor coolant system)
Reactor coolant pump shaft break	Eliminated by design
Reactor coolant pump seizure	Reduced consequences
Spectrum of RCCA ejection accidents	Eliminated by design
Design basis fuel handling accidents	No impact

Table 4 IRIS response to PWR Class IV events [4]

The implementation with an acceptable cost of these safety features is possible only on SMR. For instance the adoption of an integral reactor coolant system (impossible to be adopt in a LR) eliminates the large loop piping required for other designs, and thus the potential for postulated large loss of coolant accidents is avoided by design [4].
The result of this approach emerges with the computation of the Core Damage Frequency (CDF): for IRIS CDF is $1x10^{-8}$ [20], lower than other GENIII+ LWR reactors (for example for AP1000 CDF is $5{,}1x10^{-7}$ [21]).
The economic impact of security improvements can be assessed considering the Monetary Damage per Energy value [22] and correcting it with the likelihood that a severe accident (such as core damage) happens. The choice to represent this probability with the CDF is suggested by the fact that the core damage is the most severe accident which can affect a nuclear power plant.
The indicator obtained is the MDE Expected (MDEE).

$$MDEE = MDE \cdot P_{event}$$

Where *MDE* is the severe accident economic impact value for nuclear option, equal to 1,65 US$/GWe•a [22]; P_{event} is the likelihood that the event "core damage" happens, inclusive of the multi-sitting effect[d]. As described in par.2, the relative impact (RI) is calculated as

$$RI_{LR} = \frac{MDEE_{LR}}{MDEE_{SMR}}$$

$$RI_{SMR} = \frac{MDEE_{SMR}}{MDEE_{SMR}}$$

Therefore the relative impact equal to 12,75, according to Table 1, receives an impact judgment very higher, and the score assigned is 1.
Results obtained, using this rationale, are shown in Table 5.

	P_{event} (events/yr)	MDEE (US$/GWe•a)	Relative Impact	Impact Judgement	Score
LR	$5{,}1x10^{-7}$	8,42E-07	12,75	*Much Higher*	1
SMR	$4x10^{-8}$	6,60E-08	1	-	5

Table 5 "Security improvement" factor: absolute and relative impact.

Both the reactor sizes improved security to a very low level of risk[e], but the difference between them holds over, due to the introduction of the safety features discussed previously. Therefore the new NPP represent the safest way to produce electrical energy and the outstanding performance of SMR could be the key for the reduction of the EPZ as discussed in section 4.6.

4.2 Demand growth during the long period

This factor quantifies the impact of growing demand in the long period (during the years). It has to be assessed how the size of the capacity extension affects the investment: small plants allow to better following the demand, granting a

[d] The comparison takes place considering the same power installed. So for every AP1000, there are 4 IRIS, and P_{event} for the first is its CDF, while P_{event} for the second is $4x10^{-8}$.
[e] Percentage security improvement is 98,5% for LR and 99,9% for SMR, considering a reference value of the CDF equal to $5x10^{-5}$, that is the value of the current plants [21].

better timing and therefore minimizing the Cost of Non Satisfied Demand[f] (CNSD). In fact, the faster demand can be increased, the earliest revenues can be obtained. During the period in which demand increases, investor losses market opportunities equal to the difference between the market "theoretically" available and the net power installed. CNSD that quantifies this aspect is:

$$CNSD_{i,t} = m_{i,t} \cdot PM_{i,t}$$

This cost is obtained by multiplying the margin for the investor in the plant i at the time t ($m_{i,t}$) with the potential market for the plant i at the time t ($PM_{i,t}$). The margin is the difference between the price of electricity[g] on the market [23] and the Levelized Unit Electricity Cost - LUEC[h]. Where LUEC values are taken by the results obtained from a research group of Polytechnic of Milan: SMRs' cost is about 15% higher than the LRs' one, considering a Weighted Average Cost Of Capital - WACC of 10%.
The potential market is the difference between the total electricity demand and the actual evaded demand. For the total demand trend, looking for example at the Italian market it has been considered the increasing of electric power need for the period 2009-2014, that is 2%/year in average [24]. While the evaded demand is equal to the quantity produced because the plant produces only the quantity required.
In Table 6 are summarized the results obtained.

	Absolute Impact	Relative Impact	Impact Judgement	Score
LR	$m_{LR} \cdot PM_{LR,t}$	4[i]	*Much Higher*	1
SMR	$m_{SMR} \cdot PM_{SMR,t}$	1	-	5

Table 6 "Demand growth" factor: absolute and relative impact.

Startup Time to Market of SMR is faster, so opportunity costs are not lost.
The LR has a worst performance because of the gap that is created during the period that must spent before increasing the capacity, as it can be seen in Figure 6.

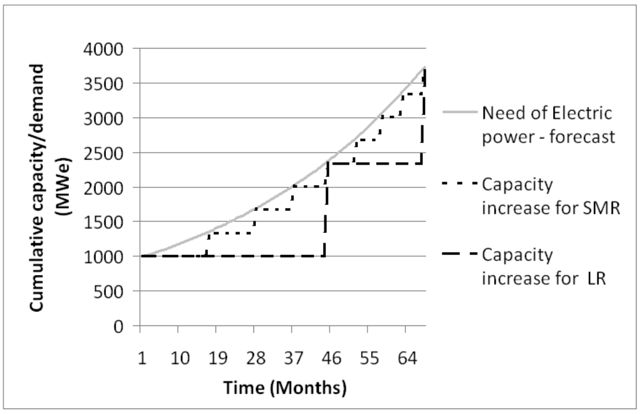

Figure 4 Following demand strategy for SMR and LR.

4.3 Licensing time

The licensing process of a nuclear power plant follows a procedure specific for each country. For instance a US plant has a licensing procedure decided and implemented from the US NRC (Nuclear Regulatory Commission) which summaries the process in [25, 26].
"In the past, in the US nuclear power plants were licensed under a two-step licensing process. This process required both a construction permit and an operating license.
An application for a construction permit must contain three types of information:
(1) preliminary safety analyses,
(2) environmental review
(3) financial and antitrust statements.
In addition, each application must include an assessment of the need for the power plant".
Let's consider now the final licensing. "Final design information and plans for operation are developed during the construction of the nuclear plant. The applicant then submits an application to the NRC for an operating license.
The application contains a final safety analysis report and an updated environmental report. The safety analysis report describes the plant's final design, safety evaluation, operational limits, anticipated response of the plant to postulated accidents, and plans for coping with emergencies" [25].
As always assumed in the analysis it will be performed a comparison among two options:

1. Construction of a stand Alone Large Reactor
2. Construction of four identical SMR.

Since all the SMR are identical is oblivious that the same steps in the licensing process, after the first units become redundant. For instance when the design for the first units is approved is high probable that the design for the second unit (perfectly identical to the first) will be approved, unless the normative changes.

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[f] Opportunity cost incurred for having a market and not a production.
[g] Considered as constant in the period analyzed: 70 euro/MWh, the average value on the Italian electricity market in 2007.
[h] LUEC is the average electricity price required to fund the construction, operation, fueling, and decommissioning of any type of energy power plant. The value considered is already inclusive of the multi-siting effect and it is determined considering a SMR of 335 MWe (IRIS size) and an hypothetic LR of 1340 MWe (equal to four IRIS).
[i] The relative impact varies in the period considered, so it has been reported an average value.

Therefore if this step is required it will be almost just a formal act[j]. The same approach applies also for the environmental review and the final licensing. Therefore, assuming the licensing time equal for the LR and the first SMR, and shorter for the further SMR, the average licensing time for an SMR units is shorter.
Mooz [27] shows as longer construction permit issuance may imply higher construction cost due to inflation (if there is a deflation, the effect tips over). However on the basis of Mooz study [27] there is the hypotesis of an inflation of commodities and labour. This is true worldwide for labour, but is not always true for commodities which have a not streightforward cost escaltion and can, in some period, have a deflations. For this reason, being conservative, we assumed an equal probability of inflation and deflation, therefore the Impact Judgement is “Appr. Equal”. However it´s necessary to underline as a shorter licensing process allows for sure a better “time to market”.

	Absolute Impact	Relative Impact	Impact Judgement	Score
LR	± x% of cost of construction	1 ± Δ	*Appr. Equal*	5
SMR	0	1	-	5

Table 7 “Licensing time” factor: absolute and relative impact.

4.4 Electric grid characteristics/Market dimension

This factor refers to the adaptability of the reactor size to the grid extension. Typical markets that will take advantage from SMR deployment are countries with a population requiring electricity in remote locations. Some islands have difficulty to supply electricity to other islands separated for different miles from the ocean. Some countries have internal zones with a scarce housing density, where is not convenient a grid extension or the cold water reserve is not sufficient for the functioning of a large plant [14].
In these cases the quantification is straightforward since the SMR is the only design that can reap profits in the market; therefore the impact is “very higher” (Table 8).

	Impact	Impact Judgement	Score
LR	Not construction	*Much Higher*	1
SMR	Construction	-	5

Table 8 Impact of electric grid characteristics.

On the other hand there are countries, like most of the European countries, with a population distributed on the entire territory. A site for a LR must have an appropriate grid, on the opposite the SMR can fit where is not feasible an extension of the current electric grid for LR or the extension is very expensive. In order to quantify this factor we present a methodology valid worldwide. However the necessary data are country dependent, therefore all the analysis is “country dependent”. Italy has been chosen as reference country.

STEP 1. – Gathering of information about the net power installed in the country

This step aims to gather the information about the electricity market. The essential information includes the net power installed with thermoelectric and nuclear plant (Table 9).

Technology	Net power installed [MWe]
Thermoelectric	69.692
Nuclear	0
Hydroelectric	21.117
Geothermic	670
Other renewables (mainly wind firms and photovoltaic plants)	2.789

Table 9 Net power installed in Italy for technology considered. [24]

STEP 2. – Global Market definition

For many countries, like Italy, the market for the construction of new power plants is mainly for the substitution of existing plants[k]. In other words we assume that the Power installed for renewable energy is maintained for the renewable energy, and the power installed in Thermoelectric plus nuclear will be replaced by thermoelectric plus nuclear. Therefore for Italy, the market of Thermoelectric plus nuclear is 69692 MWe.

STEP 3 – Specific Market definition.

With the Italian grid constraints a Large Plant, in most of the cases, can be built only where a large plant already exists (substituting this one), whereas Small plants can substitute both large plants and be scattered around to substitute other small plants.
Table 10 presents the complete list of the Italian Large plant. The total power of all the plant together is 28886 MWe, equal to the 41% of the total capacity. On the other hand the market available for the Small plants is 69692 MWe equal to 100%. It is reasonable to assume that this percentages are not going to change in the short term, therefore they could be considered as the basic data to perform the analysis.
This result does not depend on the technology, but the conclusion is that for Italy the market for the small plants is 2.5 higher than for Large Plants. This situation varies among the countries: for instance in France almost all the power installed comes from LR, therefore the SMR do not reap any advantages; however the methodology applies as well.

[j] For this considerations we do not focus on a specific country, this is a general logical assumption. This approach is valid even considering the new combined licensing process. An application for a combined license may incorporate by reference a standard design certification, an early site permit, both, or neither. This approach allows early resolution of safety and environmental issues. [25]

[k] It has been showed later that this hypothesis do not bias the analysis, since is a good approximation to assume that the percentage of renewable energy will be constant in the next years.

Utility	Plant	New Power (MW)
A2A	Cassano d'Adda (MI)	1000
Edison/Edipower S.p.A.	Brindisi (BR)	1280
	Sermide (MN)	1140
	San Filippo del Mele (ME)	1280
	Turbigo (MI)	1740
Endesa/Elettrogen S.p.A.	Monfalcone (CE)	976
	Ostiglia (MN)	1485
	Tavazzano Montanaso (LO)	1280
Enel S.p.A.	Fusina(SO)	1120
	La Spezia (SP)	1280
	Malcontenta (VE)	1120
	Montalto di Castro (VT)	3600
	Piombino (LI)	1280
	Presenzano (CE)	1000
	Rossano Calabro (CS)	1740
	Termini Imerese (PA)	1245
	Torrevaldaliga, Civitavecchia (Roma)	2640
	Tuturano (BR)	2640
Enipower S.p.A.	Ferrera Erbognone (PV)	1040

Table 10 Large Italian Power Plants. [28]

	Absolute Impact (Percentage of potential market dimension)	**Relative Impact**	**Impact Judgement**	**Score**
LR	40	2.5	*Much Higher*	1
SMR	100	1	-	5

Table 11 "Electric grid characteristics" factor: absolute and relative impact.

4.5 Equivalent power availability

When the reactor is offline, it could be necessary to find an equivalent power on the electric market, where the demand cooped with and supply and the price is determined with the balance value (spot price) [29].

If

$$\textit{price of purchase} \leq \textit{average spot price}$$

and

$$\textit{price of purchase} = \textit{LUEC}$$

the differential cost of acquiring electricity from the electric market will be:

price of purchase (proposed, = LUEC) – *average spot price*

The generation costs of LR (p´) and SMR (p´´) are obtained with a model developed from Economics group of the Polytechnic of Milan. Those results shows that p´´ is about 15% higher than p´, considering a WACC of 10%.

Considering an average spot price of 70 euro/MWh[1] (average value on Italian electricity market in 2008), is possible to compute the absolute impact with the following formula:

Absolute Impact = Average Spot Price – Technology Generation Cost

Table 12 summarizes the results. LR has the worst performance due to the higher gap between price and LUEC. Therefore

- the equivalent power purchasing is less convenient respect to SMR option (with more plants).
- if any power is purchased the marginal profit lost is greater for LR than SMR

	Absolute Impact [€/MWh]	**Relative Impact**	**Impact Judgement**	**Score**
LR	40% higher than SMR	1,39	*Higher*	3
SMR	-	-	-	5

Table 12 "Equivalent power availability" factor: absolute and relative impact.

4.6 Public acceptance

Public acceptance of nuclear power is the attitude of the public towards the deployment of this technology [30]. Different studies have been led about the risk perception of nuclear power by the public. European and American experts has analyzed factors that influence this risk perception [31, 32], showing that it varies between public and experts themselves. According to Korean studies, public acceptance of nuclear power has been related with the types of interviewers, with their education and the communication media used [33]. Chinese experts consider that benefits, risk and trust (in governmental agencies and nuclear experts) influence contemporaneously the public attitude [34]. All these studies are qualitative and highlight the factors that affect public opinion, suggesting possible ways to improve it. The only quantitative model developed is the Chinese one [35].

The idea that public acceptance can be improved with new SMR is due to security improvement (CDF reduction), environmental impact improvement (confinement time of the radioactive waste reduction) and proliferation resistance improvement [15]. Considering the social indicators identified by the Paul Scherrer Institute [11], the factor/impact areas taken into account are summarized in Table 13.

[1] This is the average value of the electricity in Italian market in 2008. Nuclear power plant are baseload plant, therefore provide power of the most of the year, consequently the average value is a reliable assumption since few days with uncommon temperatures value do not change the overall result.

Factor *i*	Acceptability dimension represented by factor *i*	Social indicator associated	Absolute weight of factor *i*	Relative weight of factor *i*
EPZ (security)	Judgment on operative risk	Risk aversion	15%	43%
Waste	Judgment on waste risk	Confinement of critical waste	15%	43%
Proliferation and protection	Judgment on terroristic attack/sabotage	Proliferation resistance	5%	14%

Table 13 Relative weight of the differential factors calculated on the basis of the absolute weight of the factor associated [11].

In a recent document the IAEA [36], proposes a way for the EPZ reduction for advanced plants. The proposal is based on two considerations: "

1. the very high level of safety characteristics of the Advanced Light Water Reactors (ALWR) versus the old plants;
2. the fact that the prescribed emergency planning is not based upon quantified probabilities of accidents but on public perceptions of the problem and what could be done to protect health and safety: in essence, it is a matter of prudence rather than necessity."

Consequently the IAEA [36] proposes a new methodology based on combination of the deterministic, probabilistic and risk management approach, which would enable consistent evaluation of advanced reactors, giving credit to their enhanced safety features.

Then the document applies the methodology for IRIS: "The IRIS Safety-by-Design™, with the elimination of the potential for several accident scenarios represents the improvement in overall defense in depth that *will enable a reduction in the emergency planning zone requirements.* IRIS, which is designed to comply with the current licensing requirements, is actively investigating the possibility to take credit of its safety by design and risk-informed design philosophy to potentially obtain a relaxation of the EP (Emergency Planning) requirements."

The document also points out that "deemed possible to reduce emergency-related site requirements for advanced plants, while at the same time providing a protection to the general public equal to or better than that provided by the current generation of NPPs and current regulations.

Achieving licensing with this new objective would offer significant societal and economic benefits to the general public and plant owners/operators, *including increased public acceptance of nuclear power, since nuclear plants will be treated as any other power plant*". [26]

The second aspect considered as differential for public acceptance assessment is the proliferation resistance and physical protection of the facility. Increasing these aspects public judgment on possible terroristic attack or sabotage to the nuclear facility may become more reasonable. Charlton [37] produces a report that can be considered the most relevant for this theme, leading an analysis for different technologies and synthesizing the parameter in a likelihood scale from 0 to 1, where the highest is the value, the highest is the proliferation risk. For a typical PWR of GEN III (LR case) this value is 0,07, while for a PWR with a batch loading of the fuel the parameter becomes 0,06 (SMR case[m]).

The third aspect that has been considered is the waste reduction. PWR waste doesn't depend on reactor size, but considering a GEN IV SMR (e.g. VHTR-Very High Temperature Reactor), an improvement in the confinement time can be observed. In fact, [38] shows that VHTR technology allows to reduce radiotoxicity per ingestion (after 25 years of confinement) from 8.788 Sv of a typical PWR (LR case), to 3.956 Sv (SMR case). It's important to highlight that this consideration, contrarily to the rest of the analysis, refers only to GEN IV reactors, and mainly to VHTR. However without considering this advantage the overall result of this factor does not change.

The quantification for these aspects is not straightforward. Every social indicator listed below represents every single factor considered, with a weight determined through experts and public considerations.

The values of these indicators are shown in Table 14.

Factor *i*	Acceptability dimension represented by factor *i*	Indicator	LR value	SMR value
EPZ	Judgement on operative risk	Binary variable	1	0[n]
Proliferation and physical protection	Judgement on terroristic attack/sabotage	Proliferation risk	0,07	0,06
Waste	Judgement on waste risk	Radiotoxicity per ingestion after 25 years of confinement	8.788 Sv	3.956 Sv

Table 14 LR and SMR value per each indicator considered.

Every factor has been quantified according to the most adequate indicator. So those values have to be standardized and weighted to be summed (Table 15).

Factor (weight%)	NON Acceptability (LR)	NON Acceptability (SMR)
EPZ (43%)	43	0
Proliferation and physical protection (14%)	14	12,2
Waste(43%)	43	19,3
Total	100	31,5

Table 15 Total non acceptability for each size of reactor.

The values in Table 15 are obtained standardizing the values in Table 14 to have comparative measures, weighting the standardized amounts with those in the fifth column in Table 13 and summing them. The overall a-dimensional result is an index of non acceptability.

[m] Most of the SMR of GEN III+ and GEN IV allows a batch loading of the fuel thanks to their design characteristics [8].

[n] Considering the possible elimination of EPZ for SMRs.

The higher value for LR is due to the great incidence of the EPZ presence and the great importance that public gives to this factor. Also the waste has a greater score for LR.
In Table 16 are summarized the results obtained, where “NON acceptability” parameter represents the level of non acceptability of an option, therefore the highest is the value, the lowest is the public acceptance.

	Absolute NON acceptability	Relative NON acceptability	NON acceptability judgement	Score
LR	100	3,2	*Much Higher*	1
SMR	31,5	1	-	5

Table 16 “Public acceptance” factor: absolute and relative value.

The economic impact of the public acceptance has been already discussed. It is important to highlight that this quantification is based on a correct informative campaign to the public transmitting the possible advantages of SMR. The public support of the nuclear plant is fundamental, as it can be deduced from European experience (e.g. in Italy). In Italy any reactor has been constructed after the Chernobyl accident and all the national plant has been decommissioned because of public irrational fear of this technology. In the bargain, another proof of the public acceptability importance is the fact that NRC licensing process counts public presence. An example of successful public opinion management is Finland, where Olkiluoto inhabitants have agreed with the realization of a new nuclear power plant (that is currently under construction). It’s obvious that, besides correct information, also an adequate economic compensation plays an important role for acceptability.

5 Results

The research provides two basic set of results introduced in Paragraph 2. The first concerns the prioritization of the factors (i.e. which are the factors weighting the most). The second concerns the reactor size and technology. Therefore the integration aims to put together all the different factors providing a synthetic final result. Since the factors’ weights are scenario dependent also the final results will be related to the considered scenarios.

5.1 Results – factors prioritization

The Prioritization phase obviously shows that improvement in the nuclear safety and public acceptance are the accounts weighting the most in the environmental centred-case and socially centred-case (Figure 5). This result was expected since the other factors have a slight influence on the environment and social aspects. Considering the external factors there is a strong overlapping among these scenarios. This is a reasonable since the safety strongly impacts both on the environment and the society, whereas, for example, licensing time influence mainly the investment’s profitability.
On the opposite considering the Economy centred-case the order of magnitude of the different factors is comparable. This can be explained considering that all of them impact in a certain way on the investment’s profitability.

The Base Case weights the same Economic, Environmental and Social concerns, therefore it points out as safety improvement and public acceptance are still the most important factors, even if the relative difference has been reduced respect to the environmental centred-case and socially centred-case.

5.2 Results – integration

It has been found in chapter 4 that, for each factor, the SMR is always the best choice or at least receives the same score of LR. Therefore the comparison among innovative SMR vs. LR shows as SMR performs better than LR in all the scenarios (Figure 6).
In particular the SMR performs better in the environment and socially centered scenario thanks to the innovative feature and the enhanced safety aspects that, as showed before, have the greater importance in these scenarios.
In the economy centred case the relative advantage of SMR comes also from the “Demand variation” factor, i.e. thanks to the smaller size the SMR are more suitable to follow the grow in a liberalized market. This aspect has a great importance for the investors since they can deploy the reactors matching the market.
Considering all these aspect the overall evaluation (Base case) points out as, beyond any doubts, the external factors are a competitive advantage for SMR respect to LR.

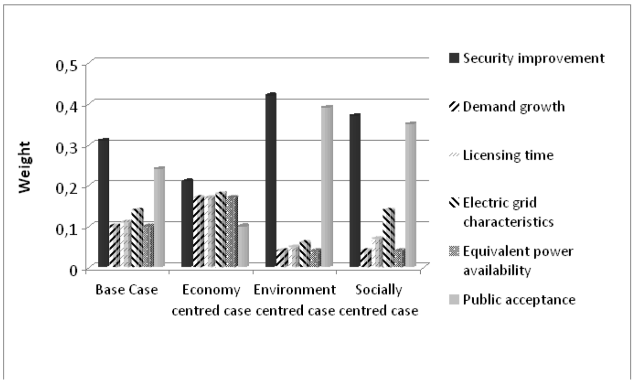

Figure 5 SMR vs. LR. Factors weights according to the different scenarios

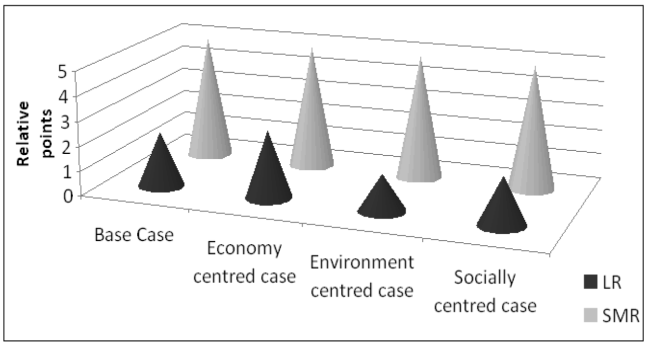

Figure 6 SMR vs. LR. Results in the different scenarios

6 Conclusions and further developments

This paper represents a first quantification of the external factors, i.e. factors, some of them not monetary (as public acceptance), not directly and easily included in a standard investment evaluation.

The results show that the new SMR perform much better than the LR. For this new generation of NPP the advantages come from the enhanced safety, the possibility to better follow the market and a potential greater public acceptability.

These results are fundamental for the nuclear sector because, as reported in chapter 3, nuclear technology performs below the other generation technologies in two important factors: public acceptability and risk of severe accidents. However the nuclear data used to obtain these results are mainly related to actual reactors. The SMR present an outstanding improvement just on these aspects. As reported at the point 4.1 the new SMR are much safer than GEN III+ reactors and even more respect to GEN II. As showed in section 5 the enhanced safety gives a strong competitive advantage to the SMR, therefore it can provide a great support to the so called "nuclear renaissance".

The logical consequence is that these new reactors are particularly suitable for counties whit a limited grid. In some states (as Italy) the adverse public opinion is one of the main barriers to the construction of NPP. The public opinion is conditioned by irrational fears; however the correct communication of the enhanced safety of the new reactors could contribute to overcome these fears. Under this prospective is clear that a reactor with the enhanced safety features can well represent a technological breakthrough.

In this research field there are two main areas for further developments. The first is related to the factors quantification and should include a better quantification of the public acceptability, Co-generation options and Sitting constraints

The second stream is related to the factors prioritization. The expert elicitation is necessary to work out more accurate weights for the different scenarios and the integration of these results in the overall profitability open model.

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