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Competitiveness of Small-Medium Reactors: a probabilistic study on the economy of scale factor

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Abstract - *Smaller size reactors are able to play an important role in the worldwide nuclear renaissance. The major disadvantage of those new reactors – the unit size - would label the small-medium size reactors as not economically competitive with larger plants. But, the economy of scale law applies only if the designs are similar, which is not the case here, since the SMRs are designed with original and innovative solutions not accessible to large size reactors: the IRIS reactor is used as an example of small medium reactors (SMR), but the analyses and conclusions are applicable to the whole spectrum of SMRs. The aim of this paper is to present latest advances in the differential economical assessment of Generation Cost of SMRs compared to LRs.*
The international literature has started to present studies focused on the two major differential accounts of Levelized Unit Electricity Cost - Capital Costs ($/kWe) and Operation and Maintenance Costs ($/kWh) - providing deterministic values for the main cost drivers (i.e. economy of scale, multiple units, learning during construction, design characteristics and modular build, shorter construction time for CC, economy of scale location of the plant, number of units, capacity factor, learning by doing, plant obsolescence for O&M costs). Since the modern SMR market is in the early stages of development, it is necessary to consider also the uncertainties associated to current estimates of those cost drivers. When available, the uncertainty has been integrated in the Open Model assigning a probabilistic distribution to the input value of each cost driver. As Far as other cost drivers are concerned, parametric analyses are still under development and uncertainty analyses are not available: thus, conservative but realistic values for both of them have been assumed. Some reasonable future scenarios have been assumed, considering the private operator perspective for a single plant investment and postulating, among the others, electricity wholesale prices, number of units in the same site, delay between the construction of further units. The MonteCarlo simulation was applied to assess the competitiveness of SMRs, obtaining the probabilistic curves of the evaluation parameters: payback time, NPV, financial exposure, leverage and project balance have been chosen to evaluate the differential economical assessment of SMRs vs LRs.
The results clearly confirm that, under certain assumptions, the competitiveness of SMRs is supported not only by an inferior financial exposure, a smoother project balance, and a shorter leverage, even with an inferior NPV, but a reduction of the financial risk related to those parameters.

I. INTRODUCTION

Nuclear power can play a relevant role in the strategic response to the growing energy needs, since it can be considered as the only GHG free baseload electrical energy. Considering then the size of emerging economies - in terms of availability of capital and limited electrical grid - , the enhanced safety and the technical simplicity, Small and Medium Reactors (SMRs) seem to be one of the most promising opportunity for the nuclear reinassance in the near future. However, they are still not seen as a competitive option because of the conventional axiom of the economy of scale: the larger the size, lower the costs.

Since the economy of scale law applies only for similar design plants, this is no applicable here, where SMRs present innovative concepts and characteristics not accessible to large reactors. Considering the growing interest in this new type of reactors, the IAEA has started in 2006 a CRP (Coordinated Research Project) to assess the economical competitiveness of SMRs.

As part of the IRIS (International Reactors Innovative and Secure) development [1] – a new concept reactor with characteristics similar to those of SMRs -, Westinghouse had already lead to the investigation of the economical competitiveness of SMRs, involving in the study utilities, private investors, universities and research centres.

The Open Model developed by Politecnico di Milano [2] aims at providing an assessment of the differential investment value between a large Gen III+ reactor and a series of SMRs, starting from the hypothesis of installing the same generation power. Indeed, it is more interesting to establish and quantify the effect of the parametric cost drivers that make the difference between the specific cost (in $/kWe) of 1 kWe of power installed in a large reactor

(LR) and the specific cost of 1 kWe of power installed in an equivalent group of SMR units, rather than the absolute specific cost of 1 kWe installed in a nuclear power plant (NPP) implementing a specific design.

To this end, a literature review of cost drivers has ben carried out, referring to the two main cost items of the Generation Cost: the Capital (also known as investment costs) and Operating & Maintenance (also known as O&M) costs, which together count for more than 70% of the total generation cost of electricity generated by NPPs. Using a preliminary version of the Open Model, quite promising results have been returned: a ratio of investment costs, between SMRs and LRs, in the range 1.0 and 1.16 and a ratio of O&M costs of about 1.19 have been estimated [3-4].

Nonetheless, at this stage of the research, all the parameters considered in the differential analysis, and thus the results, were only deterministic: uncertainties were not modeled yet, but we know that they are a critical issue in the nuclear industry (as it can be seen in section II for Capital Cost). This paper starts to deal with the assessment of cost drivers uncertainties, providing a framework to associate a probability distribution to each cost factor (Section III), starting from the state-of-the art research in the economical assessment of SMRs and the available data in the scientific literature (as done in Section IV for the economy of scale factor of Capital cost).

II. CAPITAL COST UNCERTAINTIES

II.A *Issues in estimating the capital cost*

The history of cost estimating of Capital cost in Nuclear Power Plants (NPP) is really poor, at least for what concerns the United Stated and more generally, the First-of-a kind (FOAK) units installed. Table I shows that, at least in the US, the average over budget in the construction cost of NPP, is more than 200%.

TABLE I

Table I Actual vs Budget Cost: the US case. DOE, 1986 [5]

Construction Starts		Average Overnight Cost		
Year Initiated	No.of Plants	Utilities' Proj. [$/KWe]	Actual [$/KWe]	Overrun (%)
1966 to 1967	11	612	1,279	109
1968 to 1969	26	741	2,180	194
1970 to 1971	12	829	2889	248
1972 to 1973	7	1,220	3,882	218
1974 to 1975	14	1,263	4,817	281
1976 to 1977	5	1,630	4,377	169
Overall Average	13	938	2,959	207

Considering a more recent experience of nuclear power plant construction, the new nuclear power plant in Olkiluoto is suffering an over budget of almost 50% (the 2003 estimate was 4.48 G$ - 2,800 $/KWe - shifted in the 2008 to 6.3 G€ - 3,955 €/KWe). Olkiluoto is the First-of-a-kind (FOAK) plant in Europe after 20 years and the escalation cost of commodities in the recent years contributed to the over budget. Accordingly, several authors and institutions have shifted their investment cost estimates from 2,000 $/KWe (suggested few years ago) to almost 5,000-7,000 $/KWe , as shown in Table II.

Table II Table modified from (Schlissel and Biewald, 2008 [6]) and integrated with (World Nuclear News, 2009 [7]) and (Vaillancourt et al., 2008 [8])

Forecast	Overnight Cost [$/KWe]	Total Plant Cost [$/KWe]	Total Plant Cost – 2 units [billions$]
DOE (2002)	1,200 – 1,500		
MIT (2003)	2,000		
Keystone Center (2007)	2,950	3,600 – 4,000	
Moody's Investor Services (2007)		4,000 – 6,000	
Florida Power & Light (2007)	3,108 – 4,540	5,492 – 8,081	12.1 – 17.8
Vaillancourt (2008)		2,646 – 4,998	
World Nuclear News (2009)	3,441	6,335	14

The cost escalation from budget to actual cost is not a prerogative of NPPs, but is quite common in large projects and Flyberg studied carefully the causes [9]. Technical explanations deal with unreliable or outdated cost data and the use of inappropriate forecasting models. But, considering technical explanations, the actual data (i.e. the effective final investment cost) should be scattered around the budget value (i.e. the estimated final investment cost), with an equal distribution of under and over estimates. However actual distributions of inaccuracies are consistently and significantly non-normal, with actual costs significantly higher than budget costs. Therefore Flyvbjerg argues that psychological and political explanations better account for inaccurate forecasts. Psychological explanations account for inaccuracy in terms of optimism bias; that is, a cognitive predisposition found with most people to judge future events in a more positive light than is warranted by actual experience. Political explanations, on the other hand, explain inaccuracy in terms of strategic misrepresentation. However with more accurate studies it is possible to progressively reduce the uncertainties in cost estimation. This aspect has been covered by the American Associate of Cost Engineers International (AACEI) and Electric Power Research Institute (EPRI). As reported in Table III they propose to reduce the cost uncertainty with more accurate (and expensive) studies: the range of values will likely be asymmetric because of undesired and unforeseen events that may move up the total cost during the plant construction.

Table III Uncertainty in the cost estimation. Source: American Associate of Cost Engineers International (1997) [10] and EPRI (1993) [11].

AACEI	AACEI exp.	EPRI	EPRI Sugg.
End Usage	Accuracy range	Designation	Contingency
Concept screening	Low: -20%/+ 50% High: +30%/+100 %	NA	NA
Feasibility Study	Low: -15%/-30% High: +20%/+50%	Simplified estimate	30-50%
Authorization or Control	Low: -10%/-20% High: +10%/+30%	Preliminary estimate	15-30%
Control or Bid/Tender	Low: -5%/-15% High: +5%/+20%	Detailed estimate	10-20%
Check estimated or Bid/Tender	Low: -3%/-10% High: +3%/+15%	Finalized estimated	5-10%

III.B. *Comparison between the uncertainty cost of a LR and a series of SMR*

It is reasonable to assume that the cost of the FOAK unit is the highest and most affected by uncertainty. Moreover, it is also reasonable to assume that it is more unreliable to estimate the cost of NPPs with innovative designs compared to a NPPs with more classical designs. Under this perspective it is possible to argue that the cost uncertainty related to a FOAK SMR is higher than the one of a FOAK Generation III+ LR because in the world there are already few examples of Generation III+ NPPs, operating or under construction: in Japan, four ABWR units are in operation; in Taiwan and Japan three units are under construction [12]; some EPR and AP1000 NPPs are under construction worldwide.

On the other hand, even if there are 139 reactors with a size below 700 MWe operative around the world [13] none of them has the innovative features embedded in the new nuclear reactors, therefore they can be considered a poor reference for the cost estimation. A better way to estimate the capital cost of an innovative passive SMR is to scale the cost of a modern passive LR. However, following a top-down approach as indicate by GEN IV [14] it is necessary to include the uncertainties associated to the scaling operation.

Some uncertainties in the cost estimates are site/countries dependent: they are associated to the regulatory contest as well as the learning and the project delivery chain. It is reasonable to assume that these uncertainties are highly reduced after the FOAK units in the site. Under this perspective, when an investor wants to assess the uncertainties associated with the investment cost of the installation of a certain amount of MWe (for instance 1,340MWe), he should consider the impact of different technical solutions:

- one standalone LR of 1,340 MWe;
- a series of SMRs units (e.g. four reactors of 335 MWe each).

Indeed, in the second option, the investment cost uncertainty for the first unit is surely greater than for the LR case, but it dramatically decreases for the next units, with an "average" uncertainty potentially smaller than for the LR option (Figure 1).

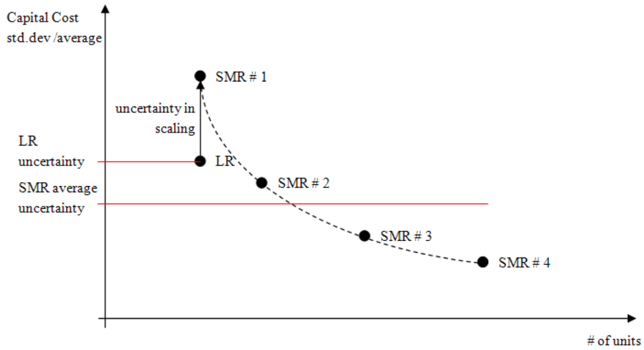

Figure 1 Reduction of construction cost uncertainty by progressive units installation (capital cost std. dev [$/kWe])

The construction of more units allows an estimation with the "class project" approach, presented by Flyvbjerg [9], that represents the best way to estimate the cost of a generic large project.

Moreover, the construction cost estimate of the NOAK units should be more reliable for the SMR than the LR since, thank to the modularization, more work is performed in the factory where the condition are more stable than in the stick-built case.

Nevertheless, modelling the uncertainty as suggested above is not sufficient, because of the structure of the Generation Cost. As widely known, four cost items are comprised in the generation cost: the investment costs, the O&M costs, the fuel costs and the decommissioning costs.

The following section will provide a framework to quantify the probabilistic distribution associated with each cost item.

III. FRAMEWORK TO ASSOCIATE A PROBABILISTIC CURVE TO ANY COST ITEM

In order to calculate the ratio between the cost of a LR and SMRs (no matter whether Capital Cost, O&M, Fuel or Decommissioning is considered), the Open Model [2] proposes to multiply a vector of values – each one corresponding to the effect of a differential parameter between LR and SMRs - greater o lesser than 1. Thus, postulating that the factors are independent variables, their multiplication can provide a reliable value for the final ratio.

For instance, considering only the capital cost, the effect of six cost drivers has been quantified: 1) unit size; 2) multiple units at a single site; 3) learning; 4) construction time; 5) match of supply to demand, and; 6) design related characteristics.

The first cost driver, unit size, will lead to a factor greater than 1 (according to the simple application of the economy of scale law): the other will have a factor lower than 1, as presented in Figure 2. Table IV presents the value of the different coefficients [2].

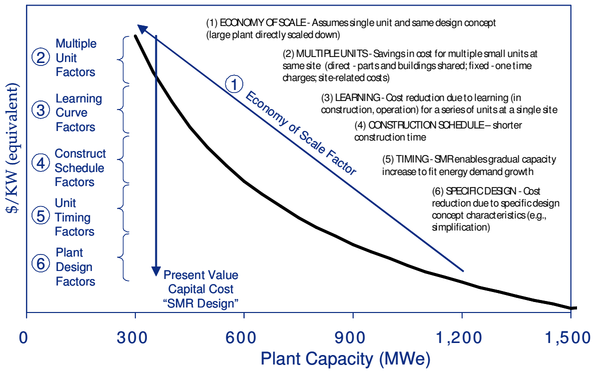

Figure 2 Potential for Small Reactors Economic Competitiveness [2].

Table IV Quantification of Factors Evaluated in SMRs/Large Plant Comparison of Capital Costs [3], [4]

Factor	Individual SMR/Large	Cumulative SMR/Large
(1) Economy of scale	1.7	1.7
(2) Multiple-unit saving	0.86	1.46
(3) Learning	0.92	1.34
(4) (5) Construction schedule and timing	0.94	1.26
(6) Design specific	0.83	1.05

SMR: One 335 MWe plant, as part of four units
Large: One single 1,340 MWe plant

The proposed procedure for including cost uncertainties into the comparative analysis of SMRs and LR investments, is organized into six steps, as described in the following:

1. Identification of the parameters for the estimation of the *i-th* cost driver.
2. Classification of deterministic and uncertain parameters.
3. Search for relevant references for the estimation of uncertain parameters, if available. Here tree cases are possible:

a. statistical curves are reported (e.g., "parameter alpha has a mean value of x and a standard deviation of y");
b. a set of observed values are reported; in this case, it possible to use a discrete distribution or, if the number of values is large enough, to interpolate these values with a best-fitting curve.
c. Both curves and values are reported; in this case a wise pathway could be to carefully consider which is the most reliable information (e.g., the most recent or related to very similar cases) and to correct the curve with more recent values.

4. Input collected information into the Open Model tool, i.e a spreadsheet that supports simulation tools (e.g., @risk);
5. Design the simulation campaign (e.g., sampling technique, number of iterations, number of scenarios) and run the simulations;
6. Analyze the results.

This procedure should be applied to each relevant cost driver of the four cost items of the Generation Cost: Capital, Operation and Maintenance, Fuel and Decommissioning Costs.

Unfortunately, at this stage of the research, the only available data in the literature concern the exponent of the economy of scale law applied in the capital cost: thus, the following section will be devoted to the application of the procedure to obtain a probabilistic profile for this factor.

III. PROBABILISTIC ASSESSMENT OF THE ECONOMY OF SCALE FACTOR FOR CAPITAL COST

Economies of scale can be quantified (assuming that the two plants are comparable in design and characteristics) using Eq. (1).

$$AC^{C}_{SMR} = AC^{C}_{LR} \times \left(\frac{S_{SMR}}{S_{LR}} \right)^{\alpha_{ES}} \quad (1)$$

Where AC^{c} is the average capital cost [$/kWe], S is the size of the Nuclear Power unit [MWe], α_{ES} is the economy of scale exponent. If the α_{ES} parameter is smaller than 1, economies of scale exist, the closer the n value is to 0, the larger the economies of scale.

Input Analysis

AC^{C}_{LR} = 1 (normalized) - deterministic

S_{SMR} = SMR size: 335 MWe - deterministic

S_{LR} = LR size: 1,340 MWe - deterministic

α_{ES} = unknown value to estimate

In order to quantify α_{ES}, an historical analysis has been made from different literature sources. Bowers et al. (1983) [15] summarizes 28 studies with an average value of 0.57 and Table V includes the results of other important studies.

It is also possible to compute α_{ES} more accurately considering the breakdown cost of the NPPs and applying the specific economy of scale exponent (α_{ESi}) to each *i-th* account.

Table V Distribution of economy of scale exponent in other studies

SOURCE	*Report o Computer Code*	α_{ES}
ORNL, 1987	Concept code	0.5
Departmen of Labor, 1982	Construction Labor Demand System,	0.63
NERA, 1982	National Economic Research Associates, Inc.. 1982	0.5
ORNL, 1983	Various authors	0.57
ORNL, 1983	Concept Code IV	0.69
ORNL, 1983	Architect-engineer study	0.70
US AEC,1974	Reported	0.68
US AEC, 1974	Calculated	0.86
DOE, 1998	Derived from different experience	0.64

The algorithm consists of the following four steps:

1. Define the breakdown cost for the Large Size reactor;
2. Compute the economies of scale for each account using equation (1) and the specific α_{ES} exponent. The main reference for the α_{ESi} exponents are Phung (1987) [16] and (EMWG, 2007) [14];
3. Sum up the accounts' values to compute the total capital cost for the SMR. The SMR is now characterized by a size S_{SMR} and an Cost AC^{C}_{SMR} (total capital cost/ Size)
4. Compute the general exponent using Eq. (2):

$$\alpha_{ES} = \frac{\ln \dfrac{AC^{C}_{SMR}}{AC^{C}_{LR}}}{\ln \dfrac{S_{SMR}}{S_{LR}}} \quad (2)$$

The result from this "account by account" analysis on the reactor of interest (e.g on the IRIS reactor chosen as example of SMRs), led to an equivalent exponent value of $\alpha_{ES} = 0.619$, coherent with the literature values. Since this value is "customised" on the IRIS reactor (335 MWe) is much more reliable than the previous ones; therefore it is possible to give a different weight to the "customised" value and to those coming from the literature. The set of values are summarised in Figure 3.

The best fitting curve of reported data is a Logistic with alpha = 0.5914 and beta = 8.92433 E-02, as shown in Figure 4. The estimated probability density distribution of α_{ES} (with the tails cut at 0.2 and 1) has been implemented into the Open Model.

III.A. Results of the analysis

The probabilistic distribution of the economy of scale exponent has been included into the Open Model, considering a specific overnight cost of a large reactor (size 1,340 MWe) equal to 3,500 \$/kWe (conservative with the most recent estimates provided in Table II) and an estimated construction time of 20 quarters. Other assumptions concerning the large reactor are reported in Table VI:

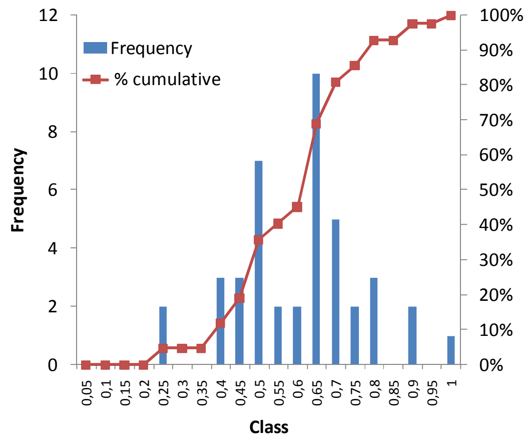

Figure 3 Pareto Chart of α_{ES} values

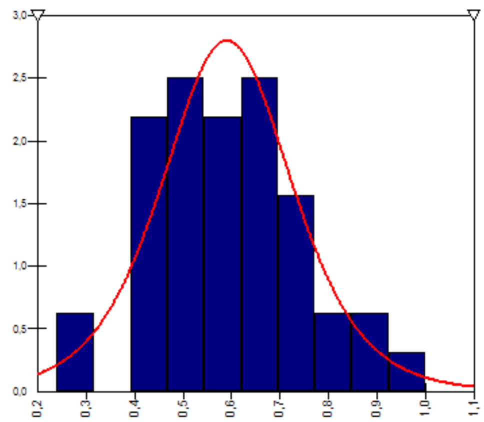

Figure 4 Best fitting curve (Logistic) for α_{ES}

Table VI Assumptions for GenIII+ LR

Load Factor [%]	100
Availability [%]	90
Operation and Maintenance [$/MWh]	9.0
Fuel Cycle – Front end [$/MWh]	8.2
D&D sinking found [$/MWh]	1.1

Then some data regarding the series of SMRs (four units of 335 MWe each) and the differential cost reported in literature [3-4] are needed (Table VII).

The investment analysis has been performed adopting a

Weighted Average Cost of Capital (WACC) as reported in in Eq. 3:

$$WACC = K_e \frac{E}{D+E} + K_d (1-t) \frac{D}{D+E} \quad (3)$$

Where:

- E is the the equity amount invested in the project;
- D/E is the financial gearing of the project;
- K_e is the rate of return required by shareholders for the equity;
- K_d is the interest rate required by debt-holders;
- t is the tax rate.

Table VII Assumption for a series of 4 335 MWe SMRs

Capital Cost differential factor	
Economy of scale	Logistic distribution
Multiple units in single site	0.86
Learning	0.92
Construction schedule and timing	0.94
Modularization and design specific savings	0.83
Other parameters :	
Operation and Maintenance diff. factor	1.2
Fuel Cycle – Front end diff. factor	1
D&D sinking found diff. factor	1.16
Load Factor [%]	100
Availability [%]	90

Exploting the capabilities of the Open Model the following hypothesis have been assumed (Table VIII):

Table VIII Assumption for LR and SMRs financial parameters

Large Reactor	
WACC	10%
K_d	9%
K_e	13%
Tax Rate	35%
Operating years	40
Construction time [years]	5
SMRs	
WACC	10%
K_d	8,5%
K_e	13%
Tax Rate	35%
Operating years	40
Construction time [years]	3

The results of the simulation with an appropriate software, such as @Risk, show that the NPV of the investment in the LR is about 752 mln$, that has to be compared to the shareholder's NPV in the case of SMRs option (Figure 5).

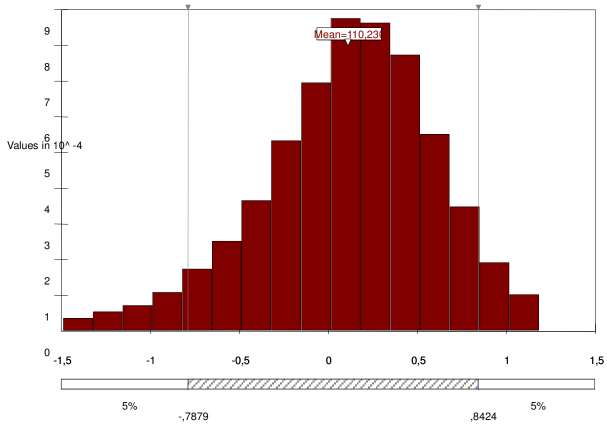

Figure 5 Probabilistic distribution of Shareholders' NPV for SMRs (thousands of $)

Figure 5 also highlights the impact of uncertainties on the economies of scale on SMRs' estimated reddtivity: the NPV ranges from -788 mln$ up to 842 mln$. The average NPV value obtained during the simulations is about 110 mln$, significantly lower than the NPV of the LR option. Indeed, a LR gets full revenues earlier than a group of SMR units, thus SMRs' revenues are much more discounted than LR's ones. Furthermore, the parameters of the probabilistic distribution of shareholders' NPV are of particular interest (Table IX).

Table IX Statistics about shareholders' NPV

Shareholders' NPV	Value
Mean	110.23
Standard deviation	486.49
Skewness	-0.51
Kurtosis	3.24
5% perc	-787.87
95% perc	842.38

From the table above it is clear that the standard deviation is considerably higher than the mean value, meaning that the economic competitiveness of an investment on SMRs compared to an equivalent LR is quite sensible to the actual value of the economy of scale factor (all other factors remaining the same), that should be carefully estimated.

Furthermore, the simulation allows to draw some considerations about the financial mix of the investment. Firstly, the average debt for the SMRs construction (distributed as shown in Figure 6 and with an average value of 825 mln$) is lower than the correspondent debt required for LR (with an average of 1,342 mln$), although the debt duration is considerably higher (9 in case of LR, 13.3 for the SMRs series).

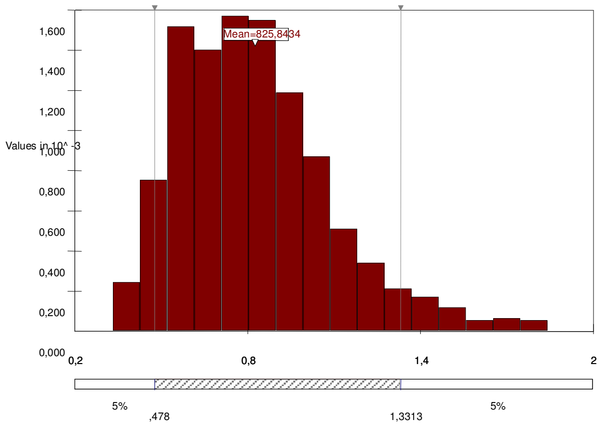

Figure 6 Probability distribution of the average debt for the SMRs option

Furthermore, assuming a basic leverage of 50%-50% for financing the LR option, it is possible to draw and compare the capital mix required by the SMRs option: the estimated probability distribution of the equity ratio between SMRs and LR is shown in Figure 7.

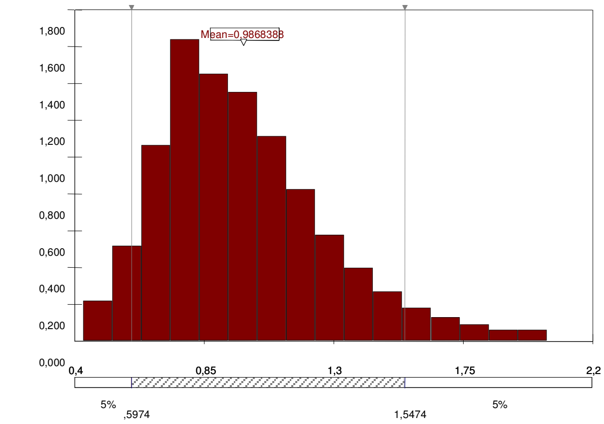

Figure 7 Distribution of the equity ratio: SMRs vs LR

It is apparent that the Equity capital required by the SMRs option could be significantly lower than for the LR option; indeed, even requiring a higher Capital cost, SMRs take advantage from the margin generated by previous units already in operation (estimated in the simulation of about 1,289 mln$). It is worth to notice that this result has been obtained choosing a construction schedule that allows the first unit to finance the last units built in the site (and with the hypothesis of respecting time and cost of construction of the first units). Thus, also the ratio between the total investment cost (E+D) required for the construction of SMRs and LR can be lower than 1. Nevertheless, this financial characteristic of SMRs is significantly sensitive to variations of the economy of scale factor (Figure 7): the 90% confidence interval of the equity ratio ranges from 0.597 to 1.547.

IV. CONCLUSIONS

This paper aims at fulfilling the gap of modeling the uncertainty within the economical competitiveness assessment of Small Medium Reactors respect to Large Reactors, and, specifically, analysing the effects of uncertainties associated with the cost drivers of the Generation Cost. Starting from a brief review of the existing attempts in estimating the capital cost, and the causes that led to a misleading estimation of the specific Total Plant cost [$/kWe] in the past literature, a quick but well-detailed framework to quantify and model the uncertainty within the cost drivers is proposed.

Considering the economy of scale factor – the most well known and important differential factor since it represents the effect of the unit size – a probabilistic distribution is established; once the uncertainty of this factor is modeled, with the support of a simulation software it is possible to assess the competitiveness of SMRs towards LR from many points of view. Particularly useful analyses refer to the NPV of the investment, the amount of Equity and Debt required by the two design options, and eventually the financial exposure.

The results of the analysis show that the total NPV of the SMRs' investment option is lower than the correspondant LR option, with an uncertainty range that may also affect the profitability of the investment.

Even considering this possible disadvantage, SMRs presents many advantages compared to LR, such as a lower financial exposure curve (measured by the average debt) and a lower total investment capital for the construction (due to the revenues from the operation of the already existing SMRs units). Nonetheless, the amount of equity and debt are parameters very sensitive to the variation of the economy of scale exponent, with values ranging from -40% up to +58% respect to the LR.

The results obtained from this preliminary analysis do not take into account the uncertainties related to other cost drivers discussed in literature (e.g. learning, multiple units in single site, modularization, etc.), that should contribute to improve the economic and financial competitiveness of SMRs when compared to LRs. It is worth to notice that neither the uncertainty in the estimation of the capital cost of the large reactor was taken into account: in this analysis values about large reactor are considered deterministic, although there are widespread evidences (as seen in Section II) of high dispersion in the capital cost entity.

For this reason, future research effort will be devoted to both the probabilistic modeling of the differential cost drivers between LR and SMRs and an evaluation of the uncertainty distribution for the input values of LR.

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