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Multiple nuclear power plants investment scenarios: Economy of Multiples and Economy of Scale impact on different plant sizes

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Abstract – *"Deliberately small" nuclear reactors are making their way on the market, not as a mere shift backwards to the small scale of first commercial reactors, but as concepts designed to foster modularization, simplification and serial production. They are proposed by manufacturers worldwide (SMART, 4S, SSTAR, mPower, Nuscale, etc.) and are also intended to address developed electricity markets. The idea of an economic attractiveness of Small and Medium sized Reactors (SMR) is counterintuitive, due to the loss of Economy of Scale on a capital intensive investment. Nevertheless a broader understanding of capital costs drivers has shaped a new concept of Economy of Multiples, that applies on multiple NPP deployment. It relies on learning accumulation to mitigate construction costs of later NPP units; design modularization to exploit the benefits of "serial" production; co-siting economies to decrease the incidence of fixed and site-related costs. We assume that smaller NPP size fosters design modularization and simplifications, with related cost savings. While the effect of modularization on construction costs has been modeled, the estimation of design-based savings may be the upmost arbitrary and controversial, but the underlying assumption is that the lower the plant size, the higher may be the "Design cost-saving factor".*

The dynamic and benefits of the Economy of Multiples of SMR have already been investigated on a case study of a stand-alone Large Reactor (LR) against four SMR deployed on a single site. The two alternative investment projects have been evaluated on their economic performance and profitability.

But Economy of Multiples is not a privilege of SMR. This work aims to analyze at what extent and conditions the Economy of Multiples holds against the Economy of Scale, when NPP of different sizes are deployed in multiple units, considering that the Economy of Multiples smoothes its benefits with the increase in number of units installed and that the maximum size of the sites is a limit to its application on LR. The limit case-study of "Very Small Reactors" (VSR) is investigated, representing a massive NPP deployment and a huge loss of Economy of Scale.

Our analysis is performed by mean of INCAS (INtegrated model for the Competitiveness Analysis of Small-medium modular reactors) Polimi's proprietary simulation code. Scenario simulations are run managing the Design cost-saving factor of each SMR fleet size as a parameter; its value is calculated in order to achieve the same level of economic performance of LR investment scenario. In other words we have determined the required design simplification effort needed by each NPP size, in order to attain the economic performance of the equivalent LR deployment scenario.

Our results show that the Economy of Multiples holds as a competitive edge for Medium and Small Reactors even when nuclear site may host multiple LR: 8-9% design cost saving is able to *grant the same economic performance of a fleet of LR, even with higher construction cost estimates. On the contrary, VSR need to achieve more stretching degree of design simplification and related cost savings (up to 15%) in order to be competitive with LR.*

I. INTRODUCTION

The so-called "nuclear renaissance" is taking place in USA and Europe in a changed framework, as compared to the first nuclear commercial era. In the nineties, the USA regulatory process has tackled market competition in the power generation sector. In the same decade, Western Europe countries undertook the privatization of the public utility industry (with the exception of the questioned case of France).

Today, submitted to the laws of financial markets, the management of the utilities is compelled to take cost-effective decisions and strategies from a financial and operating perspective. Investment strategies has to be optimized respect to limited financial resources.

The nuclear investing characterizes as a capital-intensive process, with long pay-back times and therefore a risky profile as compared to the short-term needs of private operators (IAEA, 2008). Financial risk is covered by higher cost of capital that translates into higher LUEC (Chicago, 2004). For some investors, the capital investment effort in big generating units may even be unaffordable: capital-at-risk and up-front investment need to be curbed by smaller utilities or state-owned operators of emerging countries.

In this context, new NPP concepts, as the "Deliberately small reactors", are being conceived and proposed to the international market, against the trend of power units' capacity increase, that took place in the first nuclear civil era (Ingersoll, 2009). These concepts challenge the Economy of scale paradigm, while offering innovative features in term of design modularity, passive safety and simplification (Carelli et Al., 2007). Besides from their fit to isolated, small markets with smaller electricity grids, they may also represent a suitable investment option for operators in developed markets, allowing a modular approach to the nuclear investing and flexible respect to cogeneration uses.

II. EXECUTIVE SUMMARY

Previous researches confirm that economic competitiveness of multiple SMR relies on: plant modularization, learning process in the construction and assembling, multiple units economies on fixed costs, design simplification and enhancement (Carelli et Al., 2010). Furthermore, shorter construction and pay back times of SMR relieve the investment capital exposure.

In particular, plant modularization and design simplification are fostered by lower output and plant's size (Reid, 2003). The former leads to cost-savings by higher incidence of "serial" factory fabrication; the latter accounts for further cost savings due to smaller amount of components and more efficient layout and supply chain solutions and is synthesized in the so-called "Design saving factor" .

Hence smaller NPP have features that allow to partially compensate for their loss of Economy of scale and recover economic competitiveness against larger, stand alone units, with the same power installed (Boarin and Ricotti, 2009).

In this work INCAS compares the deployment of NPP fleets of different reactor sizes, considering the Design saving factor as a parameter in the economic competitiveness analysis. Balancing the economic performance of each different reactor fleet with the LR reference fleet, the model is able to provide the Design saving factor as the degree of design enhancement necessary for smaller reactor concepts to compete with LR.

Results show that Economy of Multiples intervene to balance the loss of Economy of Scale of SMR in the lower bound of construction cost estimate. When higher construction costs are considered, the loss of Economy of Scale has higher incidence and different reactor size fleets display different capability to recover it. Very Small Reactor plants need challenging target design simplifications and enhancements to compensate it.

Simulations results show that Medium Reactors (MR) and Small Reactors (SR) economic performances are very similar: SR enjoys high benefits from modularization cost savings that fully compensate higher loss of Economy of Scale. Nevertheless, when sensitivity analysis is performed against more conservative models for capital cost factors, a gap opens between economic performance of SR and MR, the former being penalized and MR behaving like a robust option against model's uncertainty.

III. METHODOLOGY AND MODEL

INCAS cost model is based on a top-down estimation approach, where capital cost of smaller NPP is derived from a stand-alone LWR unit construction cost, assumed as a reference, with its output size. Construction costs are adjusted by mean of capital cost factors that account for the so-called "Economy of Multiples": learning process in building and assembling, modularization of the reactor concept, fixed costs sharing by multiple units on the same site. Finally, specific design enhancement and simplification allowed by smaller NPP are synthesized in a Design saving factor that further reduces overnight construction costs.

Learning is a two-variable function that calculates construction cost saving factor depending on the number of NPP units of the same type already built on the same site (on-site learning) and worldwide (extra-site learning). Like GEN IV model for learning calculation, INCAS accounts for learning accumulation in equipment assembling, material handling and human labour. Learning process in these areas evolves with different pace either the assembling and construction activity is run on the same site or has been previously run elsewhere in the world. On-site learning on equipment assembling activity allows 6% cost saving at each doubling of power installed; on-site learning on material handling and labour account for 10% and 8.5% cost saving respectively, at each doubling of the power installed (Locatelli, 2006). Learning on material handling is not exportable extra-site. Model sensitivity is run with 5% comprehensive on-site cost saving at each doubling of power installed on the same site (Fig. 1). For the purpose of this analysis we assume no prior learning from worldwide building of reactor plants.

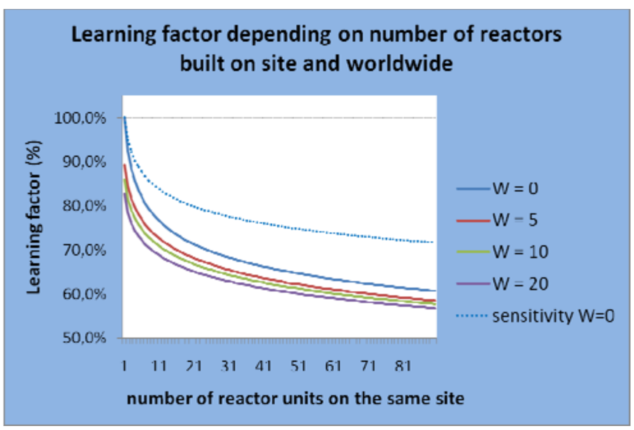

Fig. 1. INCAS Default learning factor curve, depending on number of NPP already built worldwide (W) and sensitivity curve.

Modularization curve assumes capital cost reduction for modular plants, based on the reasonable assumption that the lower the NPP size, the highest is the degree of design modularization; sensitivity analysis suggests to explore a curve with smoother decrease in unit cost below 200MWe (Fig. 2).

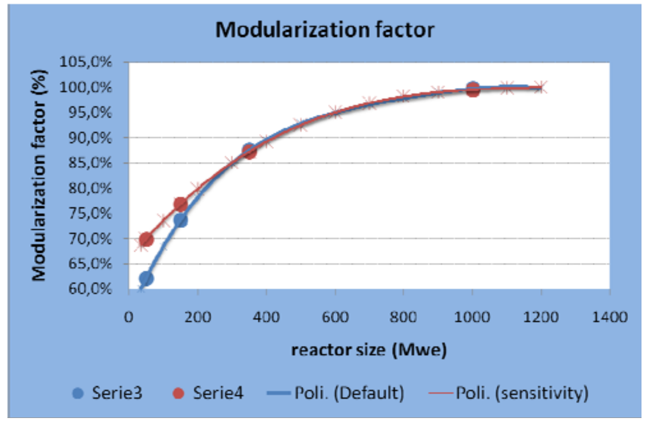

Fig. 2. INCAS Default modularization factor curve and sensitivity curve.

Multiple units saving factor shows progressive cost reduction due to fixed cost sharing among multiple NPP on the same site, until an asymptotic value of 14% for the cost saving factor of the nth unit. Sensitivity concerns a more conservative case with 10% asymptotic saving (Fig. 3).

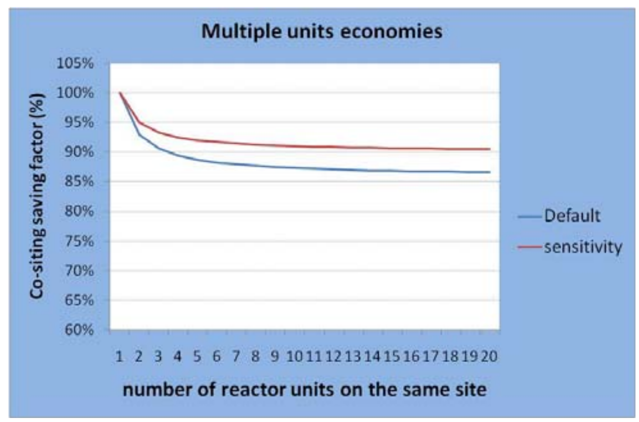

Fig. 3. INCAS Default multiple units factor curve and sensitivity curve.

Learning, Modularization, Multiple unit and Design factors allow smaller NPP to recover from loss of Economy of Scale (Fig. 4), which is modeled through the traditional Eq. (1).

$$Sf = (PWR_2/PWR_1)^{(x-1)} \quad (1)$$

Where PWR_2 is the variable reactor power, in MWe, and PWR_1 is the size of a reference LWR, in MWe; $x = 0.62$ is the scale exponent. Sensitivity is run on a 0.68 exponent, that represents a lower penalty on smalle units'costs.

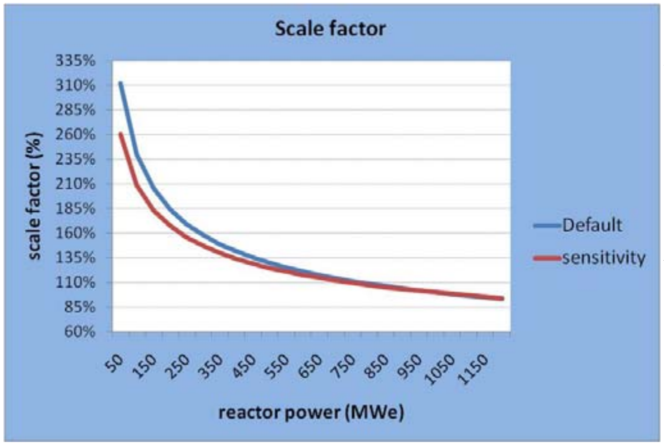

Fig. 4. INCAS Default scale factor curve

It may be argued that "Economy of Multiples" is not a prerogative of SMR; in this work multiple LR are compared to multiple SMR scenarios to investigate the differential incidence of the above mentioned capital cost factors. For this purpose, we consider different reactor plants' sizes, ranging from 50 to 1500MWe and simulate the deployment of multiple NPP units on a multi-site scenario, to attain the same 8.1GWe of generation capacity installed.

The comparative economic performance of each NPP fleet investment project is analyzed by mean of INCAS Polimi's proprietary simulation code (Boarin and Ricotti, 2010).

Nevertheless, Design saving factor may represent the upmost controversial parameter, very specific to the real NPP concept design. In a top-down approach it is provided by "expert elicitation" and may be biased by subjective evaluation. A more reliable estimation of Design factor may be obtained by a bottom-up approach that accounts for specific and detailed design references.

Without a specific design reference for each NPP size and without the knowledge of detailed design NPP concepts, we consider the Design factor as an output variable of the model, which is set to equal the economic performance of each SMR fleet to the reference 1,000MWe NPP fleet.

As a consequence, this paper provides a useful estimation of what should be the design enhancement degree for each SMR size, in order to be economically competitive with the reference 1000MWe LWR. The degree of design enhancement and simplification necessary to make SMR competitive with LR represent a sort of "target" design cost-saving factor to attain in the plant concept engineering.

Internal Rate of Return (i.e. IRR) of each investment project in a given reactor fleet is assumed as key indicator of economic performance (Hayns and Shepherd, 1991 and Oxera, 2005).

Sensitivity of results to INCAS capital cost model parameters is tested and discussed.

IV. INPUT TO THE MODEL

In this work we consider the deployment of 9GWe of nominal power (8,100MWe generation capacity) in 15 years, by multiple NPP of different LWR sizes multiple sites and perform the investment financial appraisal to evaluate the economic competitiveness of each scenario.

We consider site size of total 4,500MWe installed and a "small site" of 1,000MWe to represent the opposite situation of a country with large availability of land, resources for site-cooling and power grid capacity, and an emerging power market or a country with a high density of population and limited grid capacity, like Italy.

We analyze fleet of "Very Large Reactors" (VLR, 1,500MWe), "Large Reactors" (LR, 1,000MWe), "Medium Reactors" (MR, 350MWe), "Small Reactors" (SR, 150MWe) and "Very Small Reactors" (VSR, 50MWe). VLR may not be deployed on small 1,000MWe site scenario.

Total power installed is attained through the deployment of a different number of NPP on a different number of sites, depending on the plant size (Fig. 5 and Fig. 6).

NPP power	num. NPPs	num. Sites		site1	site2	site3	tot Mwe installed	Capacity Factor	tot Mwe generated
1500	3	2	plants	3	3	-			
			Mwe	4500	4500	-	9000	90,0%	8100
1000	9	3	plants	3	3	3			
			Mwe	3000	3000	3000	9000	90,0%	8100
350	26	3	plants	13	13	-			
			Mwe	4550	4550	-	9100	89,0%	8100
150	60	2	plants	30	30	-			
			Mwe	4500	4500	-	9000	90,0%	8100
50	180	2	plants	90	90	-			
			Mwe	4500	4500	-	9000	90,0%	8100

Fig. 5. NPP deployment on large sites (4,500MWe).

NPP power	num. NPPs	num. Sites		site1	site2	site3	site4	site5	site6	site7	site8	site9	tot Mwe installed	Capacity Factor	tot Mwe generated
1000	9	3	plants	1	1	1	1	1	1	1	1	1			
			Mwe	1000	1000	1000	1000	1000	1000	1000	1000	1000	9000	90,0%	8100
350	26	5	plants	3	3	3	3	3	3	3	3	2			
			Mwe	1050	1050	1050	1050	1050	1050	1050	1050	700	9100	89,0%	8100
150	60	4	plants	7	7	7	7	7	7	7	7	4			
			Mwe	1050	1050	1050	1050	1050	1050	1050	1050	600	9000	90,0%	8100
50	180	4	plants	20	20	20	20	20	20	20	20	20			
			Mwe	1000	1000	1000	1000	1000	1000	1000	1000	1000	9000	90,0%	8100

Fig. 6. NPP deployment on small sites (1,000MWe).

Deployment schedule is simulated to attain a uniform power installed rate over the period on each site.

SR and VSR units are considered as stand-alone NPP able to operate individually and independently each other: this assumption is questionable if the need of common civil work infrastructures is considered and the option to serve with the same turbine generator a block of multiple nuclear islands.

Electric power installed rate results as in Fig. 7 and Fig. 8.

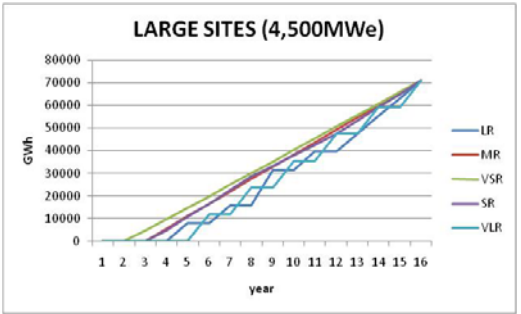

Fig. 7. Electric power installed rate on large sites (4,500MWe)

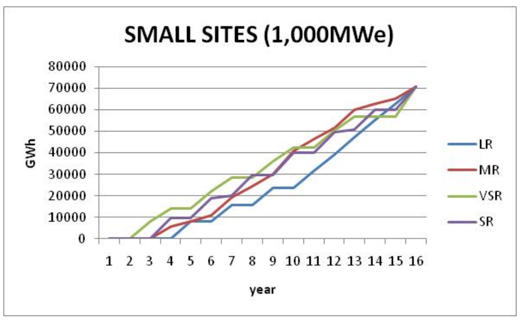

Fig. 8. Electric power installed rate on small sites (1,000MWe)

Overnight construction costs are assumed in the range of 3,000-5,000€/kWe for a FOAK LR of 1,000MWe and scaled for SMR through the application of appropriate capital cost factors (see par.3, “Methodology and Model”).

Interest expenses during construction period are capitalized in the amount of loan outstanding.

Assumptions on specific reactor data and on investment scenarios are summarized in Tab. I and Tab. II.

TABLE I

Reactor-specific assumptions

Reactor	VLR	LR	MR	SR	VSR
Power [MWe]	1,500	1,000	350	150	50
O&M [€/MWh]	9.5	9.5	11.4	11.4	11.4
Fuel [€/MWh]	5.5	5.5	5.5	5.5	5.5
D&D [€/MWh]	1.4	1.4	2.8	3	3
Constr. duration [y]	5	4	3	3	2

TABLE II

Investment-specific assumptions

Cost of Equity [Ke, %]	15
Financing mix [E/(E+D), %]	50
Debt amortization period [y]	15
Cost of Debt [Kd, %]	8
Constr. costs escalation [%/y]	2
Inflation [%/y]	1.6
Electricity price [€/MWh]	70
Electricity price increase [%/y]	2
Depreciation fixed assets [y]	12.5
Tax rate [%]	35

V. LARGE AND SMR COMPARATIVE PERFORMANCE

Economic performance of each NPP fleet has been first calculated assuming no design-related savings (i.e. 100% Design saving factor), in order to appreciate the gap between larger reactor and smaller NPP fleets profitability. Given our scenario assumptions, we may conclude that economy of multiple alone is not able to overcome the loss of Economy of Scale for smaller plants, without any design related enhancements and further cost saving.

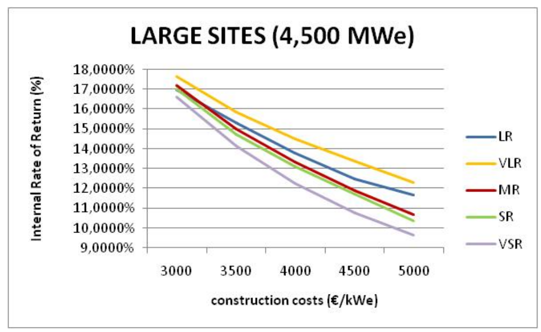

Fig. 9. Investment profitability with large sites and different sized NPP fleets

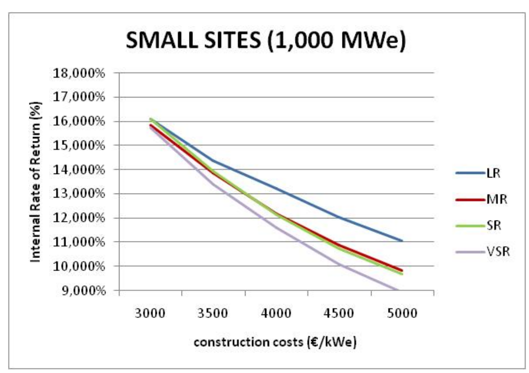

Fig. 10. Investment profitability with small sites and different sized NPP fleets

Clearly, the lower the reactor size, the lower is the profitability. It is interesting to see how MR and SR performance is similar. This is mainly accounted by the great gain in modularization attained by 150MWe as compared to 350MWe. On the basis of INCAS model's modularization curve, modularization saving factor for SR is as low as 73.7% (i.e. 26.3% cost savings), whilst MR's is 87.5%. Modularization curve decreases very sharply in the range of smaller NPP (Fig. 2). Thus, 60 SR units benefit from much higher degree of learning and modularization as compared to 26 MR plants. Loss of Economy of Scale in the output range of VSR is too huge to let them recover competitiveness, despite of even higher cost savings from modularization (Fig. 9 and Fig. 10).

Different investment profitability is reflected in cost-effectiveness of each reactor fleet, accordingly (Fig. 11 and Fig. 12).

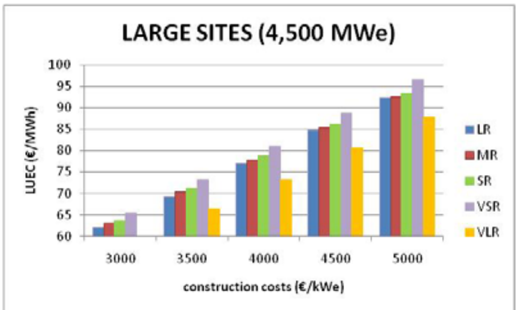

Fig. 11. LUEC with large sites and different sized NPP fleets

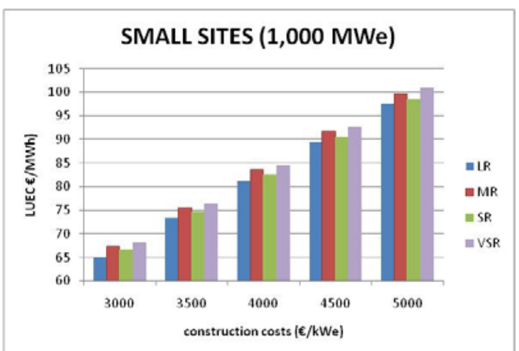

Fig. 12. LUEC with small sites and different sized NPP fleets

It is interesting to see how, given the same total reactor fleet size, the Economy of Multiples helps to decrease LUEC in large site scenarios, as compared to small site scenarios. If the same total number of NPP is concentrated in fewer sites, then learning and multiple units economies on fixed costs may be exploited in order to gain cost-effectiveness. The merit of INCAS is the tentative to quantify this intuitive behavior of the investment cases: site concentration accounts for some 5€/MWh decrease in LUEC (Fig. 12) and about 1% increase in IRR, that, given the whole investment scale, may correspond to a gain of some 800M€ up to 1.5bn€ in investment's Net Present Value (Fig. 10).

VI. DESIGN SAVING FACTORS

When economic performance of LR fleet is assumed as a reference, Design saving factor of this NPP fleet is set to 100% and Design factor of other reactor fleet sizes may be adjusted in order to attain the same level of investment profitability as LR.

Fig. 13 and Fig. 14 show that, if we assume an overnight construction cost for a reference 1,000 LWR, FOAK, stand alone, then VLR enjoy a gain in Economy of Scale, while learning and co-siting economies progressively decrease NPP units' cost. As a result the average overnight construction cost of the entire VLR fleet is so low that we have to consider a design cost "penalty" in order to align the economic performance of VLR on LR's (i.e. Design cost factor>100%). On the contrary, if the same design as LR is considered and NPP size is simply scaled down, design cost efficiency may be needed for SMR to be competitive with LR.

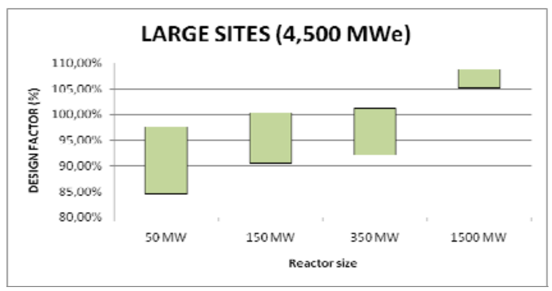

Fig. 13. Design saving factor ranges for different NPP fleets with large sites

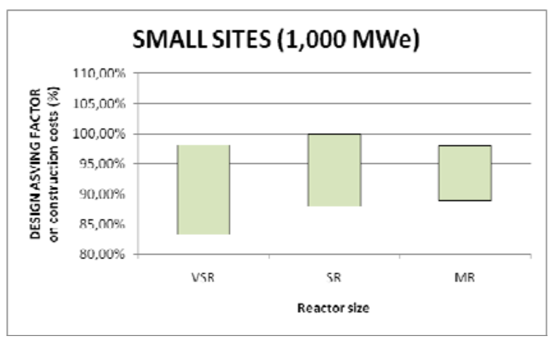

Fig.14 – Design saving factor ranges for different NPP fleets with small sites

Concerning large sites scenarios, it is interesting to see that in the lower bound of construction cost range (i.e. 3,000€/kWe) economic competitiveness of Small and Medium Reactors attains LR's without any help from design enhancement and related cost saving: in this case, specific features of modular investment in multiple smaller units is able to compensate for the loss of Economy of Scale as compared to LR fleet. On the contrary, with construction cost increasing, the loss of Economy of Scale increases its incidence and design enhancements need to bring 7.8% and 9.5% cost efficiency to MR and SR respectively, at upper bound of construction costs (i.e. 5,000€/kWe) (Fig. 13). Design cost factor has to fall in the range of 97.6-84.6% for VSR to be competitive with LR: i.e. the huge burden in loss of Economy of Scale needs a 2.4-5.4% cost efficiency from design enhancement.

Small sites scenario limits the Economy of multiple application on smaller NPP fleets and accordingly, design enhancements and simplification have to bring additional cost efficiency: MR and VSR need 98% Design saving factor to attain LR economic performance, at lower bound construction costs (Fig. 14). Design cost efficiency needed by VSR is even higher with 5,000€/kWe construction costs as compared to MR and SR. MR appear to be a trade-off between Economy of Scale, that helps this fleet to keep competitiveness in the upper bound of construction cost range (88.8% Design saving factor) and Economy of Multiples that applies its highest benefits with lower construction costs (97.9% Design saving factor).

Design-related savings need to fall in the range of 100-88% for SR: with 3,000€/kWe construction costs, Economy of Multiples displays all its benefits and SR do not need any help from design cost savings, whilst loss of Economy of Scale is limited for SR as compared to VSR.

It has to be highlighted that Design cost factors in the lower bound of construction costs shows little difference among MR, SR and VSR (98%, 100%, 98%), this difference may even be considered not relevant given the uncertainty that affect the model inputs.

Different situation arises with higher construction costs, where economic competitiveness of different fleet sizes displays significant differences: from 89%-88% for MR and SR to 83% for VSR. The smallest sized reactor plants shows all the burden of a loss of Economy of Scale: the design cost efficiency needed to overcome this burden (i.e. 17%) may be challenging to attain (Fig. 14).

VII. SENSITIVITY TO THE MODEL

Estimation curves for Economy of Multiples capital cost factors represent a sensitive input parameter in the comparative evaluation of LR and SMR, as is the Economy of scale factor.

Given the non-linearity of the functions involved in the model, a true elasticity of results against capital cost factors depends upon NPPs size and the assumption on overnight construction costs for reference NPP. Here we have assumed 4,000€/kWe as a central "Base case" overnight construction costs for a 1,000MWe LWR and tested results sensitivity against more conservative capital factors estimating curves (see par. III, "Methodology and Model"), in order to appreciate the impact of these factors on scenarios' economic performance.

INCAS simulations show that the lower is the plant size, the more sensitive are capital cost saving factors as input parameters. Learning factor is the upmost sensitive parameter leading the Economy of Multiples effectiveness. Slight change in Scale factor has the most relevant impact on economic performance indicators of smaller NPP. These evidence suggests that the lower is the size of the NPP, the highest is the uncertainty of simulations' results, due to the intrinsic uncertainty of the model parameters' estimates.

Fig. 15 and Fig. 16 show that VLR, LR and MR are more robust to cost saving factors variations.

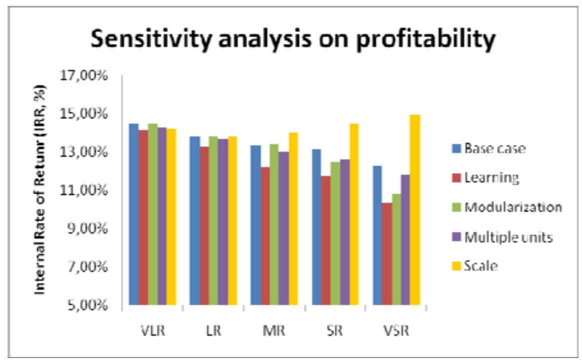

Fig. 15. Large sites scenario: IRR sensitivity to capital cost factors (overnight construction cost for reference 1,000MWe LWR = 4,000€/kWe)

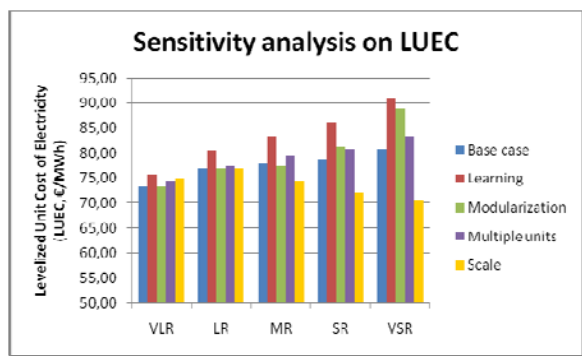

Fig. 16. Large sites scenario: LUEC sensitivity to capital cost factors (overnight construction cost for reference 1,000MWe LWR = 4,000€/kWe)

VIII. CONCLUSIONS

This work contributes to the study of comparative economic competitiveness of SMR and Large NPP plants.

Investment scenario simulations have been run, considering different reactor fleet sizes (i.e. from 1,500MWe to 50MWe) and given the same total power installed; economic performance has been measured in terms of profitability and cost-effectiveness (i.e. IRR and LUEC). Results show that with lower construction costs, Economy of Multiples is able to compensate the loss of economy of scale of SMR, but as the assumptions on construction costs become more conservative, further design efficiencies are needed in order to bring additional cost-competitiveness to smaller NPP. Among SMR, MR and SR (i.e. 350MWe to 150MWe) confirm as the most interesting investment target: 8-9% cost savings have to be provided by design enhancements and simplification in order to attain the same investment profitability as LR fleet. MR represent a suitable trade-off between Economy of Scale and Economy of Multiples paradigms. SR economic competitiveness with larger NPP mostly relies on learning and modularization benefits compensating the high loss of Economy of Scale. Finally, VSR need to achieve stretching design cost savings in order to be cost-competitive: up to 15% with construction costs assumption in the upper bound of estimates. Sensitivity analysis shows that if we question the economic model's assumptions, results are more uncertain with smaller sized reactor plants. VLR show the strongest economic performance, with the chance to even loose design cost-efficiency (Design saving factor>100%) as compared to 1,000MWe LR reference design, and keep a competitive edge on all the smaller plant sizes. Nevertheless, these scenario analysis are "static" as far as boundary conditions are considered: without uncertainty on scenario assumptions (i.e. electricity price evolution, construction delays, electricity demand, etc.) Economy of Scale is easily gaining. But when market uncertainty is introduced in the analysis and financial default depends on it, then larger monolithic NPP may increase investment risk. Further investigation should focus on the advantages of modular investment in smaller NPP, not only from the mere cost-effectiveness point of view, as in this work, but even in the investment risk perspective, in order to catch a more complete picture of the comparative economic competitiveness of Large versus SMR.

NOMENCLATURE

D&D = Decontamination & Decommissioning
FOAK = First Of A Kind
GEN IV = GENeration IV
INCAS = INtegrated model for the Competitiveness Analysis of Small-medium modular reactors
IRR = Internal Rate of Return
LR = Large Reactors
LWR = Light Water Reactor
MR = Medium Reactor
NPP = Nuclear Power Plant
NPV = Net Present Value
O&M = Operation & Maintenance
SMR = Small Medium Reactors
SR = Small Reactors
VLR = Very Large Reactors
VSR = Very Small Reactors.

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