Investment in different sized SMRs: economic evaluation of stochastic scenarios by INCAS code

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Abstract – *Small Modular LWR concepts are being developed and proposed to investors worldwide. They capitalize on operating track record of GEN II LWR, while introducing innovative design enhancements allowed by smaller size and additional benefits from the higher degree of modularization and from deployment of multiple units on the same site. (i.e. "Economy of Multiple" paradigm) Nevertheless Small Modular Reactors pay for a dis-economy of scale that represents a relevant penalty on a capital intensive investment.*
Investors in the nuclear power generation industry face a very high financial risk, due to high capital commitment and exceptionally long pay-back time. Investment risk arise from uncertainty that affects scenario conditions over such a long time horizon. Risk aversion is increased by current adverse conditions of financial markets and general economic downturn, as is the case nowadays.
This work investigates both the investment profitability and risk of alternative investments in a single Large Reactor or in multiple SMR of different sizes drawing information from project's Internal Rate of Return stochastic distribution.
multiple SMR deployment on a single site with total power installed. equivalent to a single LR. Uncertain scenario conditions and stochastic input assumptions are included in the analysis, representing investment uncertainty and risk.
Results show that, despite the combination of much larger number of stochastic variables in SMR fleets, uncertainty of project profitability is not increased, as compared to LR: SMR have features able to smooth IRR variance and control investment risk. Despite dis-economy of scale, SMR represent a limited capital commitment and a scalable investment option that meet investors' interest, even in developed and mature markets, that are traditional marketplace for LR.

I. INTRODUCTION

Up to 2011 events in Japan, nuclear option was in the wake of a new impulse to the development of nuclear power plants. The ever growing demand for electricity and the increased concern about the environmental impact of large-scale fossil-fuel plants have led to this trend, after years of stand-by in the construction of nuclear power plants. Today, after Fukushima and the related concerns about safety of nuclear reactors, and in a period of financial and economical crisis in the western countries, Small-Medium Modular Reactors (SMRs) seem to represent a more sustainable option.

IAEA has been very active in coordinating international research programs on smaller sized reactors [1;2; 3], especially in those countries that don't use nuclear power at all. The IAEA defines as "small" reactors those having less than 300 MW of electrical output and as "medium" reactors those having between300 MW and 700 MW of electrical output. Generally speaking, both types of reactors are referred to as SMRs (Small and Medium sized Reactors).According to the IAEA designation of plant sizes, almost the 30% of commercial power reactors that are currently in operation worldwide are SMRs.

Nevertheless, the focus of this research is not on SMR as mere reduced-scale versions of the large NPP, but on new models that aim at maximizing some peculiar features of design, safety and standardization in order to become economically competitive with conventional large reactors, whose success is based on the paradigm of economy of scale. Thus, they are referred to as "deliberately small reactors" and the acronym SMR is generally interpreted as "Small Modular Reactor".

This work will analyze SMRs and LRs behavior in uncertain investment scenario. The implicit assumption is therefore that both technologies are technically feasible. Nonetheless, some market scenarios exist where LRs are not an option: SMRs are the unique solution if nuclear power is to be exploited.

Some of the conditions which prevent larger plants from being an alternative for energy production are:

- Electrical grids with limited capacity; generally speaking, a grid should not be subjected to power variations in excess of 10% of the total grid capacity. So a standard plant of about 1000 MW cannot be connected to a grid of less than 10 GW.
- Remote areas or fairly scattered dwellings requiring smaller and localized sources of power; reaching them from large power stations would mean using long and expensive transmission lines.
- Limited financial capability that prevent consistent up-front investments; investors are not always able to face a capital investment of several billion dollars.
- Need of cogeneration; SMR are more suitable than LR for some applications such as desalination [3;4], district heating, industrial steam. District heating would not be feasible at all because requires the power plant to be as near as possible to the end-user area: due to safety requirements, a LR cannot be built in the middle of a populated area, whereas the SMR's increased safety level and reduced radiation source term can lead to a reduction of the emergency planning zone and to the possibility to locate the plant not far from the urban area.

I.A. SMRs ECONOMIC FEATURES

Assuming to be in a context where both the SMR and the LR options are possible, the economic factors that differentiate the cost of the two technologies must be quantified in order to assess a rational economic comparison. Since a large part of the SMRs is still in the design phase, a detailed "bottom-up" cost estimate is not yet available, at least in the open literature. This means that a simplified "top-down" approach must be adopted, accounting for all the differences in costs of the two types of reactors, through a series of multiplying factors, which increase or decrease the unit costs of a standard reference LR [6]. The average construction cost of a SMR can be then thought of as the cost of a conventional LR scaled by an appropriate overall factor whose components are here briefly summarized.

Economy of scale- Assuming that the two plants are comparable in design and characteristics, the usual correlation for economy of scale can be applied in calculating overnight costs (*OC*):

$$OC_{SMR} = OC_{LR}\left(\frac{size_{SMR}}{size_{LR}}\right)^{n-1} \quad (1)$$

Where n is about 0.6. An analogous approach is also used for the calculation of O&M specific costs, which will thus be incremented. Considering only this aspect would lead to a large increase in costs for SMRs which would make them economically unattractive. However, other factors must be taken into account.

Multiple unit factor- If multiple units are built at the same site there are advantages in terms of infrastructure sharing and better utilization of site material and human resources. For example, fixed costs about roads and infrastructures needed for power plant construction to be possible, semi-fixed costs about licensing and evacuation plans (Emergency Planning Zone costs) and site related design optimization costs can be shared. Both small and large reactors could be deployed in multiples at the same site, but the need of more SMR units to attain the same electrical output as an LR leads to a generally greater advantage related to this factor for SMR than for LR technology. Nonetheless, an evaluation case-by-case must be done.

Learning- Another important factor whose relevance is enhanced in SMR cost evaluation is learning. A NOAK(N-th Of A Kind) plant costs less than a FOAK (First Of A Kind) because of the lesson learned in the construction and deployment of earlier units. Learning can be evaluated both on site and worldwide; if an additional unit is installed in the same site, the costs will be reduced at a faster pace than if the additional unit is built elsewhere: this is because in addition to labour learning, learning in factory equipment and learning in the utilizations of materials (which arise no matter where the plant is built), there is a contribution in learning due to a better work organization on the same site, where the workers have already had experience in the construction of the previous module.

Another important characteristic of this factor is to be time-dependent, meaning that as time goes by the experience accumulated will fade away and will not be relevant to construction savings.

Design Saving- Project choices have an important impact on construction costs. Apart from direct savings on the quantity of materials used (steel, concrete, fuel) due to the smaller size, simplified designs imply a different type and a reduced number of components (for example pumps are not needed in reactors based on natural circulation).

Modularization- Modularization is directly related to the design saving factor. The construction and deployment of a larger number of standardized units reduces the need for more expensive and time consuming on-site constructions and allows factory fabrication of components at a higher degree, thus gaining benefit from mass production economies.

I.B. SMRs FINANCIAL FEATURES

Apart from these factors that are directly related to generation costs, other SMRs typical features should be taken into account about some relevant financial aspects.

Up-front investment- The reduction in total overnight construction costs per unit (due to the little electrical output) translates directly in a contained up-front investment. This might enable investors with limited access financial resources, to enter nuclear market laying out lower capital-at-risk.

Investment scalability- In relatively stable market conditions, where electricity prices and electricity demand have steady trends allowing for long term planning, the SMR modularity turns into scalability. If the demand is known to grow at a constant rate, then investments in SMRs can be sequenced (so as the last installed SMR unit has the same operational date of the hypothetical equivalent LR) or concentrated (parallel construction of all the units so as to have the plant operating earlier). In this last case, the learning effect would be almost completely loss but revenues would come earlier, so that the overall investment could be however profitable despite higher construction costs.

Investment flexibility- In uncertain market conditions, where long-term investments represent an highly risky business, the SMR modularity turns into flexibility. The smaller sizes and the shorter construction times make SMRs more readily adaptable to market conditions, both temporally and spatially. The shorter lead times allow to split the investment in a closer proximity to the market evolution: if not needed, an additional SMR investment can be avoided whereas a monolithic LR investment may result in a unexpected loss of revenues for power not taken. An additional effect of this flexibility of deployment is related to a lower cost of capital due to a perception of reduced risk by both creditors and shareholders: the lower uncertainty translates into a reduced risk premium requested by investors.

Construction schedule- Current projected schedules for SMRs are four years for the FOAK and even two years for a NOAK of some designs. This shorter construction time is due mainly to:

- smaller size,
- simpler design,
- increased modularization,
- higher degree of factory fabrication,
- serial fabrication of components.

The main effect is to reduce labour and site costs and, most of all, to shorten the Pay Back Time of each constructed unit.

Self-financing-Self-financing is a distinctive feature of multiple NPP deployment projects: staggered deployment allows for first NPP units to produce income that can finance the construction of successive modules. This reduces investors' up-front disbursement and need for loans.

Fig.1summarizes the impact of some economical and financial factors specifically on capital costs.

As far as research methodology is concerned, two critical aspects must be considered: the parameters used to drive the investment decision (Levelized Unit Electricity Cost, Net Present Value, Internal Rate of Return) and the way they are calculated (deterministic or stochastic approach).

The majority of studies and reports uses a deterministic approach in order to compute the LUEC as the key economic indicator. Blyth [7] outlines the limits of such an analysis: the LUEC accounts for the cost of generation of a single electricity unit that will be sold on the market (it's a cost-efficiency indicator). This approach does not assess the overall investment profitability that depends on electricity market and capital market conditions; a profitability indicator, such NPV or IRR, appear as more appropriated.

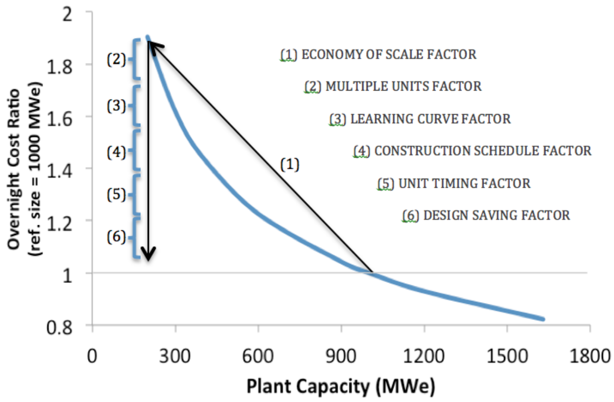

Fig. 1. Impact of some economic and financial factors on SMRs: reduction of economy of scale penalty in Overnight Costs.

Then, it is also important to consider the effect of uncertainties on the input data for costs calculation on one side (such as construction costs and fuel costs) and on revenues calculation on the other (such as electricity price, capacity factor, plant availability). Considering all these aspects, he suggests not only the NPV of the investment, as a reliable index to evaluate economic performances, but also the uncertainty related to it, assessed through a sensitivity analysis between the maximum and minimum values the input variables are supposed to take. These uncertainties are also accounted for in the Risk Premium considered in the actualization of cash flows, which is higher in nuclear technology because of a high degree of uncertainty (regulatory, plant performances, very long time horizon, etc.), thus penalizing NPV. This consideration underlines the criticality on the choice of an appropriate discount rate to calculate the NPV: in this perspective, Oxera[8] had already focused on the advantage of considering IRR instead of NPV as a suitable profitability indicator because IRR is the discount rate itself that makes NPV equal to zero.

Another important feature of IRR as opposed to NPV is its not being affected by the scale of investment: the same NPV has a different meaning depending whether the amount of the initial investment is higher or lower. If the analysis compares projects with different scale and schedule (such as LRs and SMRs), an a-dimensional indicator is therefore more significant.

Once the meaning of the different economical indicators has been analyzed, it is important to focus on uncertainty on input variables that makes the deterministic approach and the mere sensitivity analysis quite ineffective in order to grasp the economic performance of power plants. A probabilistic approach is therefore more suitable because it allows for assessing the impact of multiples uncertainties simultaneously.

Feretic and Tomsic [9] present a Monte Carlo approach to compare the LUEC of coal plants, CCGT plants and nuclear plants. The input data are uniform, triangular or have point distributions assigned on the expert judgment of the authors. The results indicate the LUEC of nuclear as the lowest (4.2-5.8 US cents/kWh and a most probable value of about 4.8 US cents/kWh), the CCGT as the highest (4.5-8 US cents/kWh, with a most probable value of about 5.8 US cents/kWh) and the coal red as in the middle (4.5-6.3 US cents/kWh, with a most probable value of 5.2 US cents/kWh). However this kind of analysis is not centered on financial profitability and do not argue about financial risk.

Roques, Nuttall, and Newbery [10] develop this aspect by calculating NPV of different technologies for 1000 MWe size plants using a Monte Carlo simulation. The mean value of input data derive from reliable sources such as MIT [11] and IEA [12]. Parameters are always modeled as normal distributed variables with standard deviation defined using literature, historical data or expert judgment. The number of iterations used in the simulation is fixed at 100.000. A first case study showed that while CCGT investment had the highest NPV, the combined effect of multiple uncertainties resulted in longer tails as compared to nuclear and, at a lesser extent, coal, indicating that CCGT investment is significantly more risky. Other simulations were then performed to show the impact of operating flexibility and different portfolios mixing.

In Locatelli and Mancini [13], a study on 335 MWe nuclear, coal and gas plants is performed with the Monte Carlo approach. As input data, literature values (historical figures and forecasts) were used and the distributions were defined with statistical methods. Then the plants were compared using four indicators: LUEC, NPV to the firm (free cash flows to the firm or unlevered cash flows), NPV to the shareholders (free cash flows to the equity or levered cash flows), IRR.

The main result is the fundamental role played by carbon tax (sequestration cost): without that cost, coal and gas technologies are more attractive than nuclear, with coal having the lowest LUEC and the highest NPV. As far as uncertainties are concerned, both these technologies seems to be the less risky considering Monte Carlo analysis. Nonetheless, nuclear investment are set in long-term scenarios and in this time-frame both electricity costs and CO2 costs are predicted to increase. The carbon tax dramatically increases the production cost of coal.

II. MODEL DESCRIPTION

The model adopted to carry out the quantitative analysis of the impact of SMRs distinctive characteristics on their economic performance, in comparison with classical LRs, is based on a cost model proposed by Carelli et al.[6], to provide an estimate value for the LUEC. It is based on an average cost function (*AC*) which depends on the size (*S*) of the plant as well as on a set of factors *X* that characterize SMRs with respect to LRs:

$$AC = AC(S;X) \tag{2}$$

In capital costs calculation, the factors *X* that have been taken into account are:

- Replication and standardization (*l*) that lead to learning effects and depends on the number of plants on the site N_n and in the world N_{world};
- Scalability and co-siting (*CS*) that depend on the number of reactors on the site;
- Financial aspects (*F*) that depend on WACC;
- Modularity and design solutions (*MD*);

An overall effect δ is identified, by multiplying the penalty factor associated to size (economy-of-scale related factor, *ES*) and the above mentioned ones:

$$\delta == \frac{AC(S_{SMR}, N_{n,SMR}, N_{world,SMR}, WACC_{SMR}, MD_{SMR})}{AC(S_{LRSMR}, N_{n,LR}, N_{world,LR}, WACC_{LR}, MD_{LR})}$$

$$= \theta_{ES} \times \theta_l \times \theta_{CS} \times \theta_F \times \theta_{MD} \tag{3}$$

Economic performance and competitiveness of multiple LR and SMR on the same site have been analyzed in [14]. This work is focused on the financial risk of SMR and LR, face to investment scenario uncertainty. A test scenario of 4 SMRs (335 MWe) has been analyzed, as compared to a single LR (1340 MWe). As far as capital costs are concerned, sensitivity analyses showed the δ factor ranges from 1:00 (best case) to 1:16 (worst case), with a value of 1:05 in the standard case.

In O&M costs calculation, a similar procedure has been adopted considering:

- labour cost;
- material cost;
- marginal cost items;

For the same scenario, the overall impact is a 24% increase in SMR operational costs, but this figure do not consider the possible specific advantages coming from technological aspects.

The economic model implemented and adopted in the INCAS code[15] is based on a Politecnico di Milano's consolidated research activity on the economic features of small-medium sized, modular reactors [16-19].

Previous works and analyses were intended to investigate the scope of the Economy of Multiples, which is emphasized by SMRs, and the benefits from modularization as a counterbalance to the loss of economy of scale.

INCAS applies a top-down approach to estimate the construction cost of SMR starting from cost reference information of a standard large LWR. The estimation relies on the modeling of appropriate scaling parameters, which apply to the reference LR unit cost to determine each successive SMR unit construction cost [15].

These factors account for:

- **Modularization cost savings**, dealing with plant engineering suitable for factory fabrication and the shift from stick built to shop built concept. Plant layout is suitable for parallel and independent modules fabrication. Modularization is possible for large monolithic reactor plants (ABWR, ESBWR, AP1000), but the lower size of SMR components and systems allow more emphasis on modularization [20].

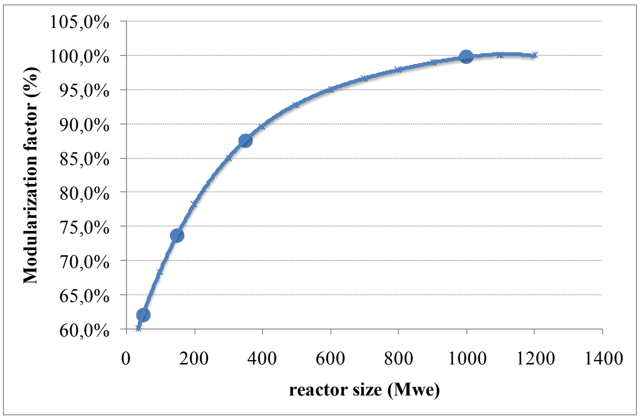

Fig. 2. Modularization factor.

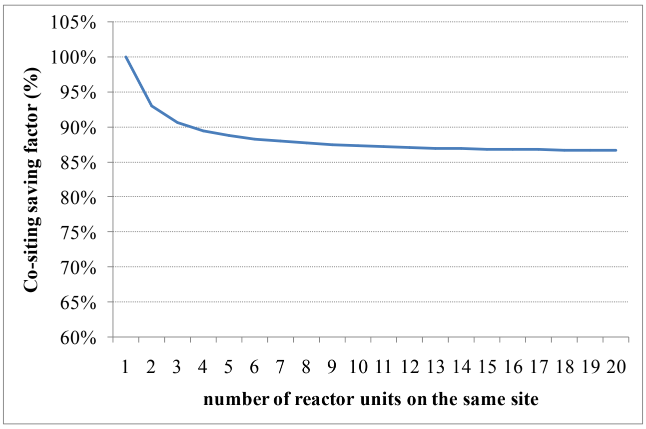

Fig. 3. Co-siting economies: site-related, fixed cost sharing by multiple units on the same site.

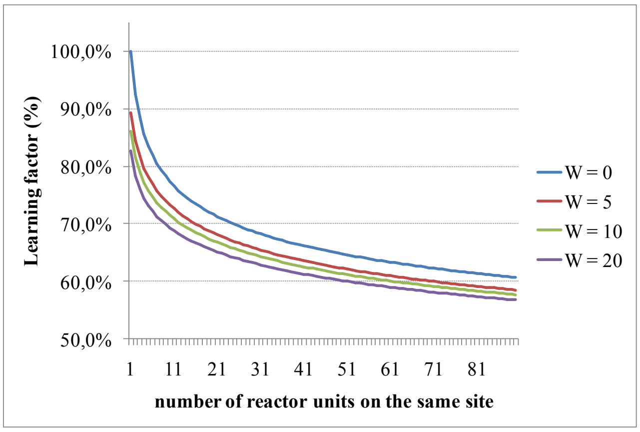

Fig. 4. Learning factor depending on number of reactors built on site and worldwide.

- **Co-siting economies** due to fixed site-related costs sharing among multiple units built on the same site [15].

- **Learning effects** on construction costs of multiple, successive NPP units [15]. INCAS model identifies and quantifies a learning accumulation process on the same site and a learning transfer from a site to another. Each cost component has a different learning elasticity: learning on factory equipment, labour and materials account respectively for 6%, 8.5% and 10% cost saving at each doubling of the power installed on the same site. Learning on material handling is considered as not exportable from a site to another. Total learning factor is calculated through the following formula:

$$K = K_{eq} \times (N_{world} + N_{site})^{-\alpha} + K_{lab} + (N_{world} + 1)^{-\beta_2} \times (Nsite)^{-\beta_1} + K_{mat}(N_{site})^{-\gamma} \quad (4)$$

where:
α = learning in factory equipment;
β_1= labor learning on site;
β_2 = labor learning in the world;
γ = learning on material handling and use;
K_{eq}, K_{lab} and K_{mat} are the percentage cost of equipment, labour and material on total cost of FOAK unit, respectively;
N_{world} and N_{site} are the number of NPP of the same type, already built worldwide and on the same site.

In addition to the above mentioned factors, design-related enhancements and simplification are considered [21-26]; better plant layout and enhanced passive safety are facilitated by lower plant's output size. Related cost-savings are included in the input analysis. For the purpose of this analysis, 90% design cost saving factor has been applied to each 300MWe plant.

Dis-economy of scale is estimated and accounted for construction costs (0.62 scale factor) leading to a +58% unit construction cost increase of first SMR against 1,000MWe standard LWR. Dis-economy of scale also applies to operation & maintenance costs (+20% compared to LR), as well as for decontamination and decommissioning annual provisions (+200% compared do LR) [17; 19; 27].

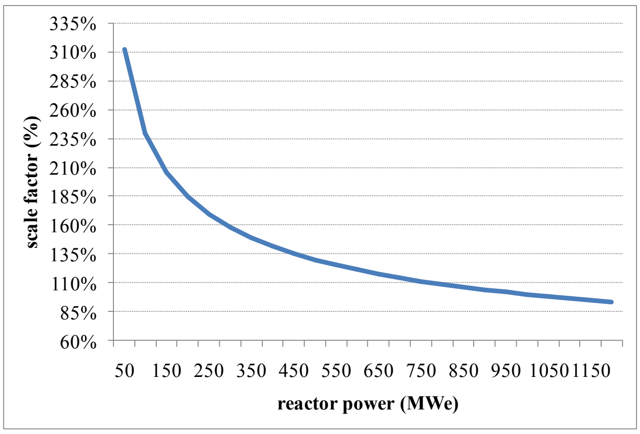

Fig. 5.Economy of scale curve.

A detailed cash flow simulation and analysis is run on the basis of a full set of scenario input data, such as electricity price, inflation, financial costs, investment financing mix, etc.

Internal Rate of Return is assumed as a suitable indicator of profitability for two alternative investment projects with a different scale and time horizon: staggered construction of SMR involves a longer period of time as compared to construction schedule of LR; capital investment costs are different.

II.A. DETERMINISTIC AND STOCHASTIC MODEL PARAMETERS

It must be acknowledged that, based on recent historical data, the uncertainty associated with some input variables, primarily overnight construction costs and duration, is dramatic.

All this considered, the investment analysis must include data uncertainty, hence input data have to be modeled by suitable stochastic distribution. Montecarlo simulation provides key indicators of the investment projects performance on the basis of a twofold approach: the expected value of the investment performance indicators and their uncertainty (i.e. distribution). The deterministic version of the INCAS code has been modified to account for the uncertainty of some input parameters. A unique, deterministic value can be affected by different sources of inaccuracy or uncertainty and can therefore bias the analysis. It becomes necessary to outline input probability distributions to include in the analysis the uncertainty on the scenario conditions or the investment specific assumptions, to provide information on the uncertainty of results. The issue has been explored and parameters on which a stochastic approach is relevant for the analysis have been chosen on three basis: (i) the importance of their impact on the results, according to a previous sensitivity analysis [28], (ii) their inherently randomness, (iii) the limited sources of historical data from which they can be extrapolated.

The set of deterministic and stochastic parameters, adopted to define and simulate a deployment scenario, is reported in Table I.

Probability distributions shapes and range limits are defined for the stochastic parameters, based on historical data and reasonable forecasts. Values collected for a standard large LWR are then compared (when possible) to the OECD figures [10] to account for their reliability. Default values for each LR and SMR reactor type, to be simulated in the deployment and investment scenario, have been estimated and assumed, at the best knowledge and by means of engineering evaluation of the Authors, according to open literature data, with the sole purpose of studying and highlighting possible trends and features of the economic and financial parameters. No judgment or ranking of different LR or SMR designs is the objective of the study.

TABLE I

Summary of deterministic and stochastic inputs.

Deterministic	Stochastic
- Power output -Operating life -Design saving factor - Cost of equity - Cost of debt - Financing mix ratio - Re-investment share of shareholders' funds - Debt amortization period - Corporate tax rate - Average depreciation period for fixed assets -Expected construction duration - Number of reactors - Number of sites - Reference power output for a standard LR - Number of reactors of the same type already built in the world - Years since the deployment of the last reactor of the same type	- Capacity factor - O&M unit cost - Fuel cycle unit cost - D&D unit cost - Delay on construction duration - Annual extra cost in case of delay - Annual inflation rate - Risk-free rate - Overnight construction cost - Annual escalation rate for construction costs

III. CASE STUDIES AND RESULTS

The investment scenarios simulated by means of the INCAS code refer to the deployment of a LR versus a set of three types of SMRs of different module size, being the power station size equal. A staggered construction schedule is adopted for the SMRs (Fig. 6).The generation capacity installed rate is different for large and modular reactors: SMR's construction is assumed diluted over 12 years to benefit from learning and re-investment of cash flows generated by early deployed in the construction of later SMRs. SMR1 modules are built as single units, while SMR2 modules in twin-units and SMR3 modules are assumed delivered in 12-unit packages.

The main deterministic and stochastic data for the reference LR (1000 MWe size) and for the different SMRs type are reported in Table II. Other stochastic parameters and corresponding values, common in the different deployment scenarios, are shown in Table III.

The electricity market evolution, during the assumed 60 years operational life cycle of the reactors, has been simulated via a mean reversion stochastic model. The parameters to be estimated in the model are:

- η, mean reversion speed;
- μ, long-run mean of electricity price;
- σ, the price volatility, which is related to the standard deviation of prices that are normally distributed with

$$E[x(t)|x_0] = \mu + (x_0 - \mu)\exp(-\eta t) \tag{5}$$

and

$$Var[x(t)|x_0] = \frac{\sigma^2}{2\eta}(1 - \exp[-2\eta t]) \tag{6}$$

The default parameters of the model were calculated based on the historical US data, with the long-run mean value updated to more recent ones:

η =0.048;

μ =68 ($/MWh);

σ = 2.9;

trend = 0.02.

Trend has been evaluated calculating the annual price increase between the same months and then computing the mean value.

Generally, NPV is used as a standard reference in order to evaluate the economical competitiveness of one or more investments. Between two alternative projects, the one with the highest NPV should be chosen.

This comparison is possible only on two conditions:

- the project develops on the same time horizon while here we deal with different investment period horizons (i.e. construction schedule of LR vs. SMRs) and therefore different commercial deployment periods;

- the capital investment is the same for all projects, while here we deal with different construction costs and therefore with different Total Capital Investment Costs.

TABLE III

Main deterministic and stochastic data for the Reference LR and for the different SMRs type.

	LR	SMR1	SMR2	SMR3
Power output (MWe)	1000	335	125	45
Units per site	1	3	8	24
Operating life (years)	60	60	60	60
Design saving factor (%)	100[1]	85.5[4]	85.5[4]	85.5[4]
Expected construction duration (quarters)	20	16	16	16
Capacity factor (%)	Beta distribution[3] Mean= 83,Std.dev= 18 Min= 36.17, Max= 100	Beta distribution Mean=95, Std.dev=20.5 Min= 36.17, Max= 100	Beta distribution Mean=90,Std.dev=19.8 Min= 36.17, Max= 100	Beta distribution Mean=90, Std.dev=19.8 Min= 36.17, Max= 100
O&M annual specific fixed cost ($/kW)	Log-normal distribution[2] Mean=68.2,Std.dev=18.85 Min= 41.07, Max= 108.24	Log-normal distribution Mean=87.6, Std.dev=23.6 Min= 52.6, Max= 138.5	Log-normal distribution Mean=104.5,Std.dev=28.2 Min= 62.8, Max= 165.6	Log-normal distribution Mean=126, Std.dev=34 Min= 75, Max= 199
Variable cost on total O&M cost (%)[2]	5	5	5	5
Fuel specific cost ($/MWh)	Log-normal distribution[2] Mean=8.2,Std.dev= 1.3 Min= 3.6, Max= 10.5	Log-normal distribution[2] Mean=5.32, Std.dev= 0.85 Min= 2.36, Max= 6.86	Log-normal distribution[2] Mean=6.8, Std.dev= 1.1 Min= 3.0, Max= 8.8	Log-normal distribution[2] Mean=8.52, Std.dev= 1.36 Min= 7.15, Max= 11.00
Num. reactors of the same type already built in the world	0[3]	0[3]	0[3]	0[3]
Time since the deployment of the last reactor of the same type (years)[3]	0	0	0	0

[1]=Represents the reference technology

[2]= Distribution has been chosen on statistical, historical data basis, or based on EMWG model.

[3]=Reference FOAK unit

[4]= Estimated by Locatelli [29].

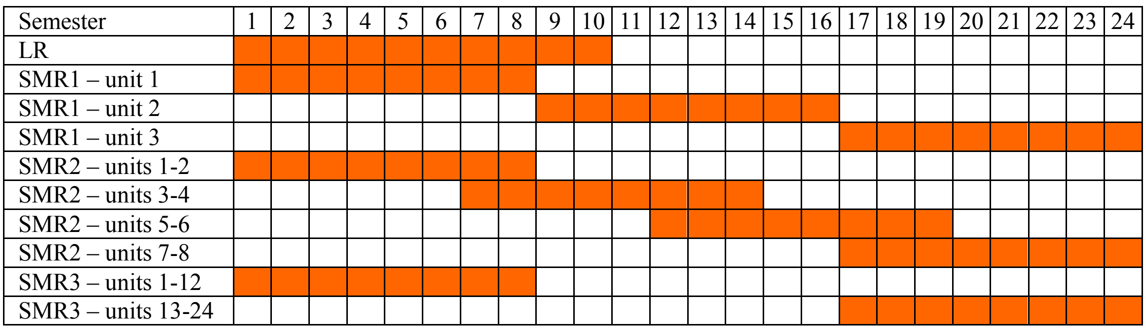

Fig. 6. Reference deployment schedule (without delays) for the different LR and SMR scenarios.

TABLE III

Input default values for main common stochastic variables.

Overnight construction cost ($/kWe)	Normal distribution[1] Mean = 3330, Std.dev = 1046 Min = 1004, Max = 5337
Annual escalation rate for construction costs (%)	Uniform distribution Min = 0, Max = 4
D&D cost ($/kWe)	Uniform distribution[2] Min = 333, Max = 1332
Risk-free rate (%)	Log-normal distribution Mean = 3, Std.dev = 1.15 Min = 0.05, Max = 6
Annual inflation (%)	Normal distribution[1] Mean=2, Std.dev=0.66 Min = 1.0, Max = 3.7
Delay on construction (months)	Normal distribution[1] Mean = 9, Std.dev = 14 Min = 0, Max = 38
Extra cost due to delay (%)	Uniform distribution Min = 12, Max = 20 Calculation in Section 4.12

[1]= Distribution has been chosen on statistical, historical data basis.
[2]=Calculated accordingly to EMWG guidelines [30].

Both these conditions are not met in the analysis. Therefore, another indicator has been chosen to evaluate the economical performances of alternative projects: the IRR.

IRR is not dependent on the scale of the capital investment and is a synthetic indicator of the project profitability with its specific time distribution of cash out/inflows.

The analysis has been made over 1500 runs to assure convergence and a standard error lower than 1% on IRR.

For SMRs projects the following severe assumptions were made:

- fixed schedule: despite possible delay of previous NPP, the construction start of following reactor of the fleet is not postponed. This assumption is severe at the extent that it limits the generation and use of self-financing;
- fixed delay: the delay distribution is the same for each reactor of the fleet, therefore each reactor, of whatever size, has the possibility to run into a delay whose duration is independent from the reactor type and its mean value is the same for large and small NPP.

TABLE IV

IRR: stochastic results.

	LR	SMR1	SMR2	SMR3
Deterministic IRR (%)	11.81	12.72	10.67	7.63
Stochastic IRR mean (%)	9.1	10.6	8.6	7.1
Stochastic IRR std dev (%)	3.7	3.4	3.7	3.3
IRR not found (times)	-	14	117	442
IRR not found (% on total runs)	-	0.9	7.8	29.5

This assumptions either is very conservative because it does not consider the option of adapting SMRs' schedule following favorable or unfavorable conditions and ignores that improved supply chain for SMRs might translate into lower construction expected delays.

The results of the simulations in terms of IRR are presented in Table IV.

The stochastic approach translates in a loss of about 2% IRR , mainly on account of construction delays.

It has to be remarked that:

- IRR variance (i.e. std. deviation) of SMR is in the same range than LR's, despite larger number of variables involved. The number of possible combinations of input values increases with the number of variables and namely with the number of reactors plants. Despite this, SMRs' IRR distribution is not more scattered than LR's.
- Loss of IRR is the same for every reactor fleet.

Nevertheless it has to be reminded that these results do not integrate the cases of financial default, arising from particularly unfavorable combination of input values.

It may be noted that in some cases IRR was not found due to particularly unfavorable combinations of input values. When capital costs are sorted from their distribution with very high values and capacity factor is in its lower bound, revenues are not able to cover all the costs and debt obligations. In these cases, the debt stock increases more and more and the situation diverges from financial recovery. This leads to investment failure. Investors lose all the capital invested as if their internal rate of return was -100%.

These cases are very few in the SMR1 scenario, more frequent in SMR2 and become more relevant in SMR3 scenario. This might also be related to the higher number of possible unfavourable combinations of input values, with the number of reactor plants in the fleet (i.e. with the NPP size decreasing).

IV. CONCLUSIONS

In the analysis carried out in the previous section, uncertainty on input values (Table III) was calculated upon historical data related to large reactors. However, the same uncertainty has been applied to modular reactors for lack of specific estimates. This approach ignores that, as a matter of fact, the specific design of modular reactors should allow for higher control in construction timing and costs.. All these aspects were not included in the analysis.

The overall uncertainty of the projects is almost the same for all the reactor types. Moreover inputs from stochastic distributions were sampled for each reactor of the fleet. This means that scenarios composed by smaller multiple modular units had more sampled input values.

Nonetheless, the IRR output distribution of SMR multiple investments has the same variance than stand-alone LR scenario.

This implies the same level of investment risk, when profitability variance is assumed as a proxy of uncertainty of financial results. However for particular combinations of overnight costs and market conditions, NPV curve vs. cost of equity does not allow to define an IRR for the NPV curve lying in the negative half-plane and never crossing the abscissa axis. This means that the investment runs into financial default and invested capital is entirely lost. This happens with SMRs that have a larger number of possible unfavorable combinations of input values . Project self-financing may be a stabilizing component relieving the project economics in unfavorable conditions. Self-financing may help to contain debt financing and avoid that debt obligations sink project economics toward the default, when low capacity factors couple with high construction costs. Moreover shorter pay back times for each SMR unit is able to limit debt interest capitalization during construction period and the escalation of debt obligations (IDC).

NOMENCLATURE

BS	Balance Sheet
CF	Cash Flow
D&D	Decontamin.& Decommissioning
EBIT	Earnings Before Interest and Taxes
EMWG	Economic Modeling Working Group
EPZ	Emergency Planning Zone
FOAK	First Of A Kind
IDC	Interests During Construction
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
LR	Large Reactor
LUEC	Levelized Unit Electricity Cost
NOAK	N-th Of A Kind
NPV	Net Present Value
O&M	Operation & Maintenance
P&L	Prot& Loss
PBT	Pay Back Time
SMR	Small-medium Modular Reactor
WACC	Weighted Average Cost of Capital

REFERENCES

1. IAEA, "Progress in Design and Technology Development for Innovative Small and Medium Sized Reactors", ANNEX IV, *Nuclear Technology Review*, Vienna (2007)

2. IAEA, *"Status of Innovative Small and Medium Sized Reactor Designs 2005: Reactors with Conventional Refueling Schemes"*. IAEA-TECDOC-1485, IAEA Vienna (2006).

3. IAEA, *"Use of nuclear reactors for seawater desalination"*, IAEA-TECDOC-574, IAEA, Vienna (1990).

4. IAEA, "Introduction of Nuclear Desalination — a Guidebook", *Technical Reports Series, No. 400*, Vienna (2000).

5. IAEA, *"Innovative Small and Medium Sized Reactors: Design Features, Safety Approaches, and R&D Trends"*. Final Report of Technical Meeting, IAEA-TECDOC- 1451, IAEA, Vienna (2005).

6. M.D. Carelli, P. Garrone, G. Locatelli, M. Mancini, C. Mycoff, P. Trucco, M.E. Ricotti, "Economic Features of Integral, Modular, Small-To-Medium Size Reactors", *Progress in Nuclear Energy,* **52**, *403*, Elsevier (2010).

7. W. Blyth, "Factoring risk into investment decisions", *working paper*, UK Energy research Centre, London (2006).

8. Oxera, "Financing the Nuclear Option: Modeling the Cost of New Build", *Agenda: advancing economics in business*, Oxera (2005).

9. D. Feretic, Z. Tomsic, "Probabilistic Analysis of electrical energy costs comparing production costs for gas, coal and nuclear power plants", *Energy Policy, 33*, 5-13, (2005).

10. F.A. Roques, W.J. Nuttall and D.M. Newbery, "Using Probabilistic Analysis to Value Power Generation Investments under Uncertainty", CWPE 0650 and EPRG 065, University of Cambridge, Cambridge, England (2006).

11. Y. Du and J. E. Parsons, "Update on the Cost of Nuclear Power", MIT Center for Energy and Environmental Policy Research, 09-004, Cambridge, MA 02139 USA, (2009).

12. OECD-NEA/IEA, "Projected cost of generating electricity", OECD, Paris, France (2010).

13. G. Locatelli and M. Mancini, "Small-medium sized nuclear, coal and gas power plant: A probabilistic analysis of their financial performances and influence of CO2 cost", *Energy Policy*, *38*, pp. 6360-6374, (2010).

14. S. Boarin, M.E. Ricotti, "Multiple nuclear power plants investment scenarios: Economy of Multiples and Economy of Scale impact on different plant sizes", *Proceedings of ICAPP 2011*- paper 11193, Nice, France, (2011).

15. S. Boarin, M.E. Ricotti, *"INCAS - INtegrated model for the Competitiveness Analysis of Small-medium sized reactors - USER'S MANUAL & TEST CASES-ver.1.1"*, IAEA CSA Report, IAEA, Vienna (2010).

16. S. Boarin, M.E. Ricotti, "Cost and profitability analysis of modular SMRs in different deployment scenarios", *Proceedings of the 17th International Conference on Nuclear Engineering (ICONE17)*-paper 75741, Brussels, Belgium (2009).

17. M. Carelli, C.W. Mycoff., P. Garrone., G. Locatelli, M. Mancini, M.E. Ricotti, A. Trianni and P. Trucco., "Competitiveness of small-medium, new generation reactors: a comparative study on capital and O&M costs", *Proc. 16th Int. Conf. on Nuclear Engineering (ICONE16)*, Paper 48931, Orlando, Florida (2008).

18. M.D. Carelli, B. Petrovic, C.W. Mycoff, P. Trucco, M.E. Ricotti., G. Locatelli, "Smaller Sized Reactors Can Be Economically Attractive", *Proceedings of ICAPP 2007*, Nice Acropolis, France (2007).

19. G. Locatelli, M. Mancini, "Competitiveness of small-medium, new generation reactors: a comparative study on decommissioning", *J. Eng. Gas Turbines Power*, 132, 10, 102906-1 (2010).

20. L. Reid, "Modeling Modularity Impacts on Nuclear Power Plant Costs", ORNL, Oak Ridge, TN (2003).

21. M.D. Carelli, L.E. Conway, L. Oriani, B. Petrovic, C.V. Lombardi, M.E. Ricotti., A.C.O. Barroso, J.M. Collado, L. Cinotti, N.E. Todreas, D. Grgic, M.M. Moraes, R.D. Boroughs, H. Ninokata, D.T. Ingersoll and F. Oriolo, "The design and safety features of the IRIS reactor", *Nuclear Engineering and Design*, 230, 1-3, 151-167 (2004).

22. M.R. Hayns, J. Shepherd, "SIRTM Seducing Size Can Reduce Costs", *Nuclear Energy* 30 (2), pp.85-93 (1991).

23. IAEA, *"Status of Innovative Small and Medium Sized Reactor Designs 2005: Reactors with Conventional Refuelling Schemes*". IAEA-TECDOC-1485, IAEA, Vienna (2006).

24. D.T. Ingersoll, "Deliberately small reactors and second nuclear era", *Progress in Nuclear Energy*, 51, 4-5 (2009).

25. R.A. Matzie, A. Worrally, "The AP1000 reactor—the nuclear renaissance option", *Nuclear Energy*, 43, 1, 33-45 (2004).

26. T.L. Schulz, "Westinghouse AP1000 advanced passive plant", *Nuclear Engineering and Design*, 236, 14-16, 1547-1557 (2006).

27. G. Locatelli, M. Mancini, "End of life of nuclear power plants: the decommissioning cost of new small medium reactors vs. large reactors", *Proc. 9th Int. Conf. on Modern Information Technology in the Innovation Processes of the Industrial Enterprises (MITIP 09)*, Bergamo, Italy (2009).

28. S. Boarin, M.E. Ricotti, "Financial case studies on Small-Medium sized Modular Reactors", *Nuclear Technology*, vol.178, May 2012.

29. G. Locatelli, "Modello parametrico per la valutazione competitiva del capital cost di reattori nucleari di IV generazione", MA thesis, Politecnico di Milano, Milano, Italy (2006).

30. The Economic Modeling Working Group Of the Generation IV International Forum, "Cost estimating guidelines for generation IV nuclear energy systems", Rev. 4.2, GIF/EMWG/2007/004, OECD/NEA (2007).