Agenzia Nazionale per le Nuove Tecnologie,
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RICERCA DI SISTEMA ELETTRICO

Valutazioni economiche con validazione-applicazione dei modelli economico-finanziari

S. Boarin, M. Ricotti, F. Vettraino

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VALUTAZIONI ECONOIMCHE CON VALIDAZIONE-APPLICAZIONE DEI MODELLI ECONOMICO-FINANZIARI

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Agenzia Nazionale per le Nuove tecnologie, l'Energia e lo Sviluppo economico sostenibile

Valutazioni economiche con validazione-applicazione dei modelli economico-finanziari

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EXECUTIVE SUMMARY

This document presents the economic evaluation of investment scenarios in NPP of different sizes. The analysis is performed through scenario simulations by means of a proprietary economic and financial model developed by Politecnico di Milano.

Due to the complexity of the analysis, scenario simulations are used as an economic evaluation tool, allowing to consider the interaction of multiple input parameters and boundary conditions on the economics of a nuclear investment project.

This study considers pressurized water reactors of different size, including Small-Medium modular Reactors (SMR). In consideration of the great interest arising by utilities worldwide for SMR and of the design effort by manufacturers worldwide in these new reactor concepts, the focus of this work is on the comparative economic analysis of Large Reactor (LR) plants and SMR. The economic performance of each investment option, LR or SMR, may be evaluated either stand-alone basis or compared basis.

Several models have been developed worldwide to perform the economic analysis of nuclear power generation, but none of them approaches the issue of SMR with their own technical and economic peculiarities. Politecnico di Milano has developed an original model and simulation tool which includes in the analysis the effect of SMR specific features and allows to overcome the bias of the economy loss of the Economy of Scale paradigm.

The model, called INtegrated model for the Competitiveness Analysis of the Small-Medium sized reactors (INCAS), is at the same time a conceptual framework for a comparative economic analysis between LR and SMR and a computational code able to run scenario simulation and quantitative results about key financial performance indicators.

The analysis applies on multiples SMR, compared to a single or multiple LR with equivalent total power installed.

The analysis performed provides for a comprehensive set of economic indicators of an investment in a NPP fleet of whatever size in different scenario conditions. It also allows to argue about the economic competitiveness of multiple SMR. This relies on: plant modularization, learning process in the construction and assembling, multiple-units economies on fixed costs, layout simplification and design enhancements fostered by lower output and plant's size. The former (i.e. modularization) accounts for cost-savings by higher incidence of "serial" factory fabrication; the latter is the effect of 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". Furthermore, shorter construction and pay back times of SMR contribute both to relieve the investment capital exposure: not only SMR are "modular" plants, but also represent a "modular" investment option, with the possibility to stagger the construction schedule of successive units and to invest the cash flows generated by the operation of early deployed units in the construction of additional NPP.

Hence smaller NPP have features that allow to partially compensate for their loss of Economy of Scale and recover economic competitiveness against larger NPP units, with the same installed power.

When deterministic scenario are considered, LR show their basically superior economic performance, based on Economy of Scale and lower overnight construction costs: static values confirm the better financial performance of LR.

When scenario conditions become stochastic and uncertainty is included in the analysis, then results are reversed: multiple SMR record higher mean profitability, with more favorable data dispersion toward positive values in right tails.

Thus, Montecarlo scenario simulations show that multiple SMR represent a "modular" investment concept that is more able to absorb unfavorable scenario conditions than monolithic LR. On account of their competitiveness with LR in terms of project profitability and on account of their better performance to scenario uncertainty, they may represent a valuable alternative option, not only in small developing areas, but also for extension or replacement of nuclear power plants installed in mature and liberalized large markets.

1 INTRODUCTION

In the framework of a renewed interest toward nuclear energy, first-of-a-kind as well as subsequent units of new generation Nuclear Power Plants (NPPs) are currently under construction and planned worldwide, after a break of more than two decades in the US and western Europe.

Nowadays, the issue of economic sustainability and profitability of new NPP projects is controversial mainly due to changed market conditions and liberalization, as compared to the first civil nuclear era.

The decay of experience in plant construction and technological advancements in reactor design play as two opposite factors in the success of nuclear investment projects.

In several countries, nuclear investment projects are left to the initiative of industrial players acting on a liberalized market.

Two of the main decision criteria for investment are the financial risk and the profitability, that are hardly predictable on account of a very extensive investment horizon and of numerous risk sources.

The economic soundness of a nuclear investment needs to be assessed against different possible scenario conditions, as a priority step to the investment decision: project simulation may contribute to understand the boundary conditions that make a project affordable and profitable from an economic point of view.

In May 2008, the Italian government confirmed its strong support to the nuclear program and declared that it would foster the construction of first new nuclear power plant within five years, to reduce the country's great dependence on oil, gas and imported power.

The government introduced a package of nuclear legislation including, among others, measures to set up a national Nuclear Safety Agency to oversight the definition of criteria and procedures for reactor plants licensing and nuclear sites identification and licensing.

The comprehensive economic development legislation was finally approved in July 2009 making nuclear power a key component of the new energy policy, with a 25% target of electricity generation from nuclear power by 2030.

A major step in the implementation process was the establishment of the national Nuclear Safety Agency in 2010.

The outcome of June 2011 national referendum was unfavorable to the planned re-introduction of nuclear power, despite the moratorium set over the legislative and regulatory measures which have been taken by the government over the last three years to allow new nuclear power plants deployment.

In line with the government energy strategy, this work has been commissioned with the purpose of exploring the economics of an investment scenario in nuclear power generation and developing an original and valuable model and tool to perform such analysis.

The economic model and simulation tool developed (INCAS) allows to investigate the economics of nuclear power, with particular focus on Small-Medium modular plants and to the comparative performance of modular PWR of different output size.

POLIMI and ENEA have contributed to the research on nuclear economic competitiveness, also within international collaborations, by exploring and modeling the Economy of Multiple paradigm. In consideration of the Italian strategy to re-open the nuclear option, scenario case studies have been already analyzed to assess different NPP deployment options.

The comparative economic performance of different NPP sizes has been approached with a twofold perspective: deterministic and stochastic analysis.

2 Economy of Scale and Economy of Multiples

The share of investment in total levelized generation cost is around 75% while the other cost elements, O&M costs and fuel cycle costs, represent 15% and 9% respectively [1].

Detailed analysis of this cost category has given a broader understanding of capital costs drivers and has shaped a new concept of "Economy of Multiples", that applies on multiple NPP deployment. This economic paradigm exploits the economy of replication, capitalizing over:

- design modularization and standardization in order to foster mini-serial factory production,
- learning in the manufacturing and assembling phases,
- fixed cost sharing among multiple units deployed on the same site.

This economic paradigm is exploited by smaller NPP to counterbalance traditional "Economy of Scale" low.

2.1.1 Modularization

Modularization is modeled assuming 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. 1).

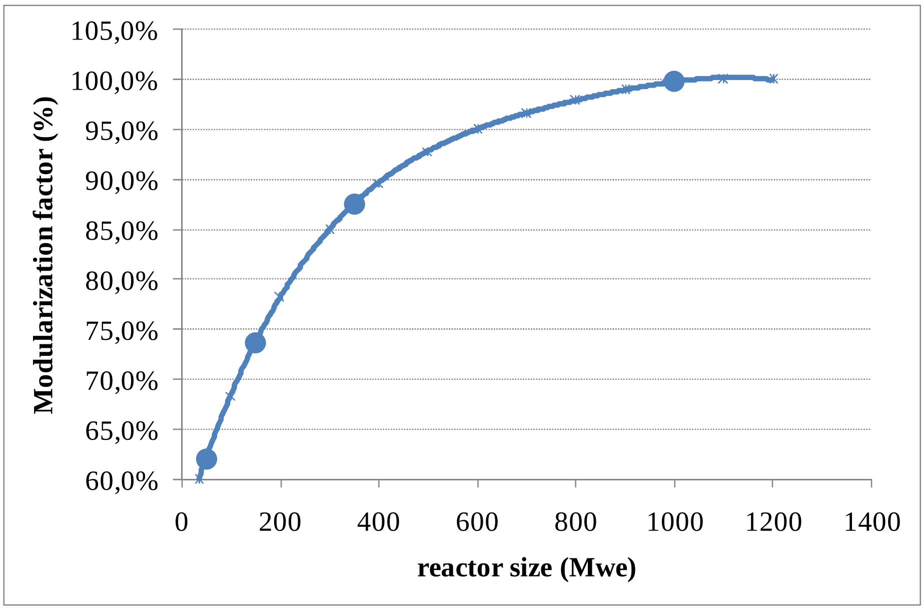

Fig. 1. Modularization factor model.

2.1.2 Learning

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.

Learning on material handling is not exportable extra-site.

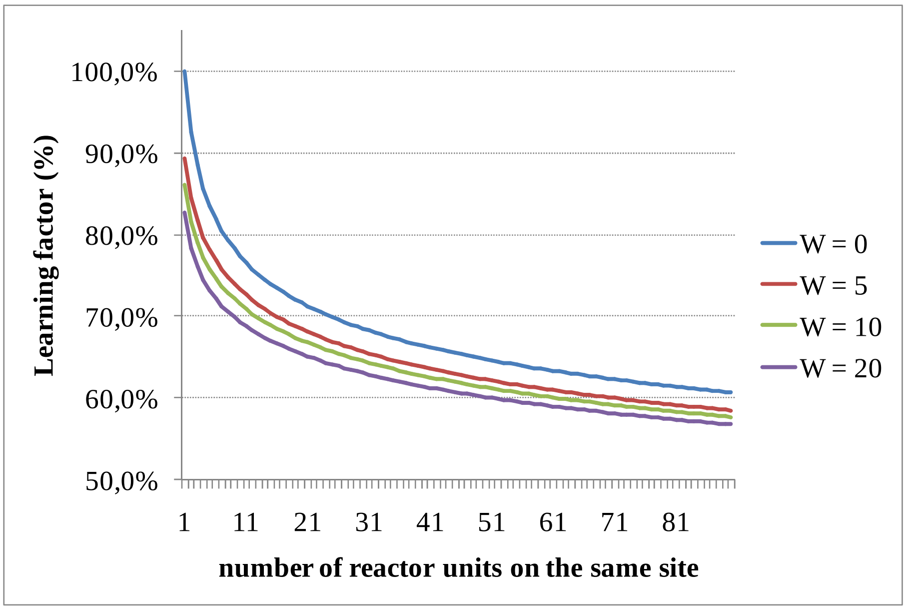

Fig. 2. Learning factor curve, depending on number of NPP already built worldwide (W).

2.1.3 Multiple units

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 n-th unit.

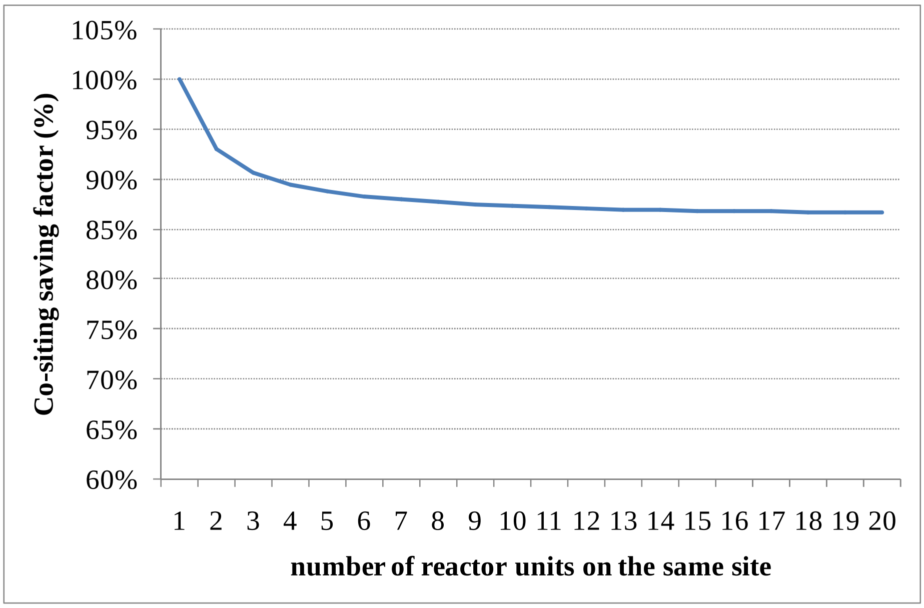

Fig. 3. Multiple units saving factor model.

2.1.4 Economy of Scale

Economy of Scale (EOS, Fig. 4) consist in a decrease of the output specific cost when the plant size increase in terms of output (i.e. electricity), because of lower incidence of fixed costs over the output unit cost. The underlying assumption is that plant of different size are based on the same technology design concept. The EOS curve is modeled through the traditional Eq. (1).

$$Sf = (PWR2/PWR1)^{(x-1)} \tag{1}$$

Where PWR2 is the variable reactor power, in MWe, and PWR1 is the size of a reference LWR, in MWe; x = 0.62 is the scale exponent.

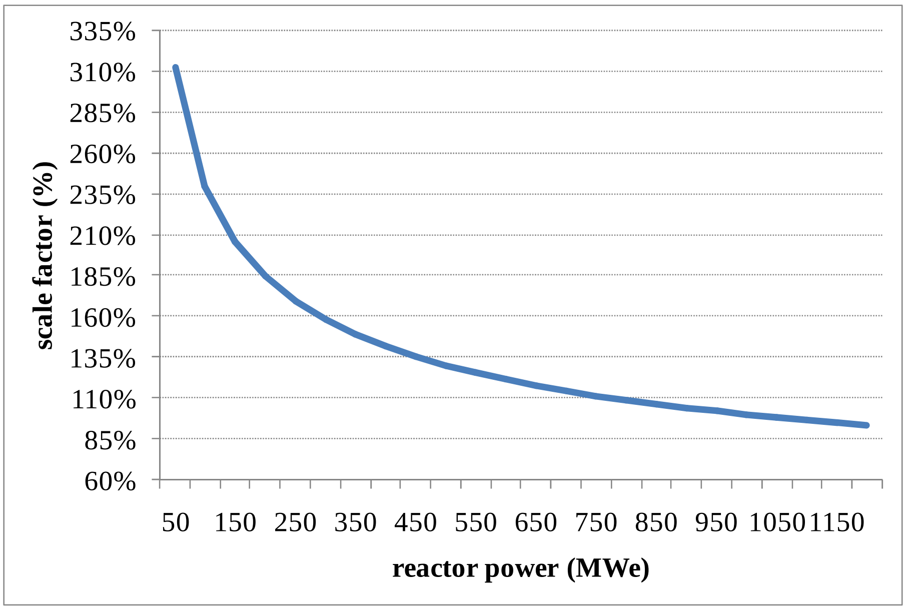

Fig. 4. Economy of Scale model.

3 ECONOMIC CHARACTERIZATION OF SMR

Small-Medium size Reactors (SMR) come to the scene where plants' size maximization has been pursued by the nuclear industry since the beginning of the nuclear civil era [2]. "Deliberately small reactors" do not represent shift backwards to the small scale of first commercial reactors nor a mere "scale-down" of current innovative LWR designs. They are designed to foster modularization, simplification and multiple-units deployment on the same site. They are developed by designers and manufacturers worldwide (SMART, mPower, Nuscale, etc.) and are also intended to address mature electricity markets, thus competing with large scale plants.

The idea of an economic attractiveness of Small and Medium sized LWR (SMR) is counterintuitive, due to the loss of Economy of Scale on a capital intensive investment. Nevertheless by exploiting the Economy of Multiples, that applies on multiple NPP deployment, they are able to smooth the loss of EOS impact. As a result, Small and Medium LWR capitalize over the operating track-record of LWR technology and exploit the economy of replication and further design enhancements available to the small scale.

SMR concepts challenge the Economy of scale paradigm, while offering innovative features in term of design modularity, passive safety and simplification [3]

Furthermore, smaller plants may represent a scalable investment with the construction of successive units diluted over a suitable timeframe. SMR shorter construction / pay back times may relieve the investment capital exposure.

When multiple, staggered NPP are built, cash flows generated by the operation of early deployed units may be invested in the construction of additional NPP. Project's self-financing may limit the up-front investment.

In addition to the above-mentioned arguments, the strong interest for SMR may be explained by the fact that for some investors capital investment effort in big generating units may even be unaffordable: capital-at-risk and up-front investment need to be curbed either by smaller utilities in developed and liberalized markets, either by state-owned operators of emerging countries.

In USA and Europe, the so-called "nuclear renaissance" takes place in liberalized and competitive market scenarios, as compared to the first nuclear commercial era. Utilities' management is compelled to take cost-effective decisions and comply to the laws of financial markets. Investment strategies have to be optimized with respect to limited financial resources; investment risk has to be edged by diversified investment portfolios.

Investments in nuclear power generation are very capital-intensive projects, with very long pay-back times: on account of this, they present a risky profile as compared to the short-term needs of private operators.

In this context, SMR are not only suitable for remote and isolated user communities, or small markets with smaller electricity grids; they also represent a suitable investment option for developed markets' private utilities that are not willing to "bet the company" on a single capital intensive project.

3.1.1 Design cost savings

As said in par 2.1.4, EOS low assumes that plants of different size are still based on the same design technology. This is not often the case: lower plant size allows for new technology solutions and enhancements that make plant of different size not comparable on the same EOS curve.

In the case of NPP, SMR are supposed to introduce design enhancements and simplifications, smaller amount of components and more efficient layout and supply chain solutions, that translate in significant construction cost savings and are represented by a "Design saving factor" to be applied on overnight construction cost base.

Such cost savings are strictly reactor type-dependent and should be calculated through a bottom-up cost estimation to account for the specific reactor design information. When detailed information is not available, specific saving factors has to be estimated on the basis of expert elicitation.

Design saving factor is a sensitive parameter because it has a significant incidence on overnight construction costs (it might account for 5-20% of overnight cost base) and therefore on the overall economics of the investment project.

This study offers an approach to the analysis of design saving factor where it is assumed as an output variable of the model: it is estimated in order to bring the economic performance of different plant sizes in line with the profitability of a large reference 1,000MWe NPP fleet, with the same total power output.

As a consequence, this study provides a useful estimation of what design enhancement degree should be the for each SMR size to be economically competitive with the reference 1,000MWe LWR.

Then, rather than an arbitrary input, the degree of design enhancement and simplification necessary to make SMR competitive with LR represents a sort of "target" design cost-saving factor to attain in the plant concept engineering.

4 REVIEW OF EXISTING ECONOMIC MODELS AND SIMULATION TOOLS

Several codes are increasingly used today for assessment studies, including some economic features, as reported in Table I. The codes usually simulate the integrated nuclear energy system of reactors and fuel cycle/waste management facilities on global, regional or national/local scale, providing the quantitative mass flow exchanges. The kernel for all analyses is based on dynamical Mass-Flow Analysis (MFA) simulation. Their capabilities in facing non-standard reactor economics is limited, in several cases.

The class of currently available dynamic simulation codes, more suited for economic and financial analysis of reactors deployment, as listed in Table II, cover indeed a comprehensive set of applications. Some tools devoted to market simulation, supported by IAEA (e.g. MAED, WASP, MESSAGE, GTMAX), provide energy planners with the assessment of different market penetration strategies for nuclear energy, to define the appropriate mix of fossil, renewable, and nuclear energy supply assets. Other sustainability assessment model-tools are specifically intended to address various areas, such as safety, environmental (e.g. SIMPACTS), proliferation resistance, economics (e.g. FINPLAN, SEMER) and apply to different generating technologies.

Economics is hence investigated as a "sustainability" concern and simulation tools aim to calculate both the investment needs for reactor and fuel cycle facilities and the resulting levelized electricity generation costs. The software simulation tools dealing with the economics of power generation fall into two main categories: energy supply market modelling and simulation of power generation investment projects. Among the latter, most of the available codes are traditionally focused on generation costs, with Levelized Unit Electricity Cost (LUEC) being the main output and economic indicator.

Only a few codes (DANESS11, FINPLAN12 and INCAS13) involve a dynamic cash flow analysis.

An economic model (INCAS - INtegrated model for the Competitiveness Assessment of SMR) has been developed by Politecnico di Milano university able to perform an investment project simulation and evaluation and suitable to compare the economic performance of SMR with respect to Large Reactors (LR).

It was born within an international research effort fostered by IAEA on SMR competitiveness. This "pilot" version has afterward been developed in order to be able to simulate country scenarios' investment analysis.

INCAS provides monetary indicators of financial performance (e.g. IRR, LUEC, total equity employed) and is conceived to combine them with not-monetary indicators (e.g. design robustness, required spinning reserve).

The original contribution of INCAS, in the synopsis of the economic simulation codes, is the capability to address the specific economic features of SMR deployment, capturing the so-called "Economies of Multiples" that counterbalance the loss of economies of scale when compared to Large Reactors (LR).

Capabilities	Code / Developer									
	COSI CEA (FRA)	DANESS ANL (USA)	DESAE UNK (Russia)	DYMOND ANL (USA)	NFCSim LANL (USA)	ORION NEXIA (UK)	OSIRIS NNC (UK)	PROGNOSIS Kurchatov & Minatom (Russia)	SuperStar Tepco (JAP)	VISTA IAEA
Equilibrium Analysis										
Single Reactor	✓ - all -									
Reactor Park	✓ - all -									
Dynamic Analysis										
Regional Reactor Park	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Multi-Regional Reactor Park	✓	✓	✓		✓	✓	✓			✓
Mass-flow analysis										
Natural U/Th use	✓ - all -									
Front-end capacity needs & use	✓ - all -									
Reactor core loading	✓ - all -									
Back-end capacity needs & use	✓ - all -									
Separated material inventories	✓ - all -									
Disposal needs	✓ - all -									
Related functionalities										
Isotopic composition	✓ - all -									
Decay heat	✓ - all -									
Reactor core management	✓	✓	✓	✓	✓	✓	✓	✓		
Economics										
Levelized generation cost	✓	✓	✓			✓	✓	✓		
Investment needs		✓	✓			✓		✓		
Cash-flow Analysis		✓								
Waste Management										
Repository impact	✓	✓		✓					✓	
Socio-political issues										
Proliferation risk					✓					
Availability										
Freeware			✓							✓
License agreement	✓			✓	✓			✓	✓	
Commercial		✓				✓	✓			

Tab I. Synopsis of integrated nuclear energy systems simulation codes

Available models	Code / Developer													
	COSI CEA (FRA)	DANESS ANL (USA)	DESAE UNK (Russia)	FINPLAN IAEA	GTMAX IAEA	INCAS POLIMI (ITA)	MAED IAEA	MESSAGE IAEA	ORION Nexia (UK)	OSIRIS NNC (UK)	PROGNOSIS Kurchatov & Minatom (Russia)	SEMER CEA (FRA)	SIMPACTS IAEA	WASP IAEA
Generation cost model	✓	✓	✓		✓	✓			✓	✓	✓	✓		
Market model					✓		✓	✓						✓
Investment model		✓		✓		✓								

Tab II. Main features of the economic simulation codes

5 INTEGRATED MODEL FOR THE COMPETITIVENESS ANALYSIS OF SMALL MEDIUM SIZED REACTORS

5.1 General structure

INCAS economic model is based on a Polimi's consolidated research activity on the economic features of small-medium sized, modular reactor plants, with the participation to international consortium for the development of the IRIS (International Reactor Innovative and Secure) reactor plant concept.

The general architecture and development strategy of INCAS code is summarized in Fig.1.

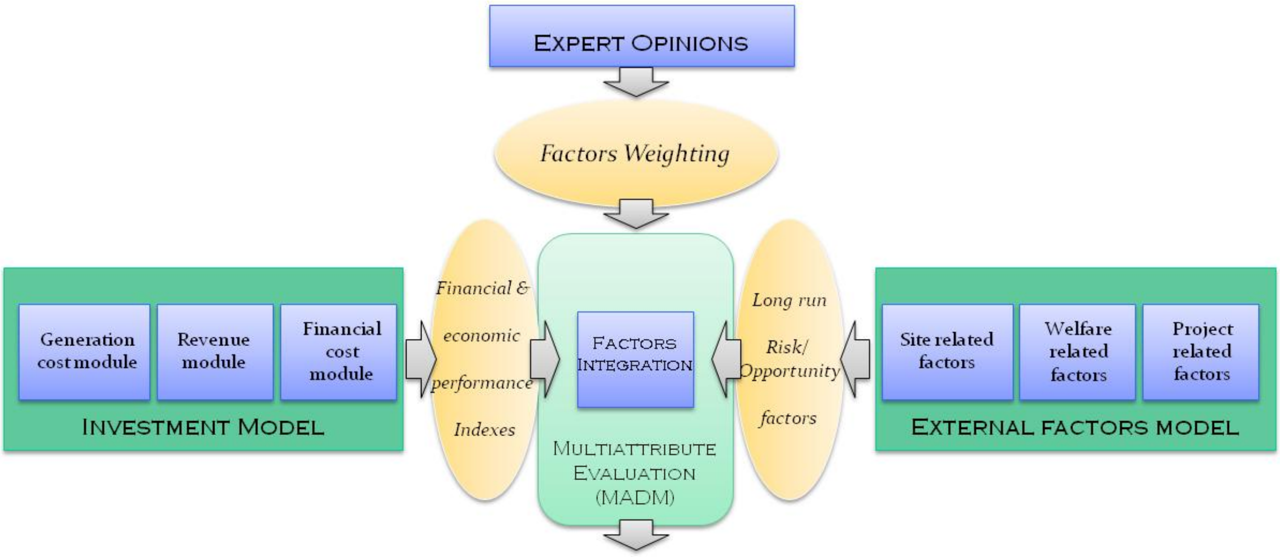

Fig. 5. General architecture of INCAS code

INCAS' Investment Model is a simulation code developed in Matlab that is able to perform the financial simulation and analysis of an investment case in a NPP fleet on a multi-site scenario.

It is based on a Discounted Cash Flow model and provides a full set of indicators of the investment's financial performance (e.g. IRR, NPV, cash flow profile, debt duration, PBT, etc).

The "External Factors Model" deals with factors usually not included within the investment evaluation (e.g. security of fuel supply, public acceptance, environmental impact), because they are not under direct control of the investor or they are hardly quantifiable. Nevertheless they strongly influence the life cycle and the feasibility of the project itself. Financial and External Factor model's outputs are then combined through a Multi-Attribute Evaluation process in order to define the overall attractiveness' score of an investment scenario.

The "External Factors Model" is currently under construction. To activate the MAE process an expert elicitation is needed in order to set the priority of attribute of different nature.

5.1.1 Generation Cost Model

Generation Cost Model calculates construction costs and operating costs, including Operation & Maintenance (O&M), fuel cycle and Decontamination & Decommissioning (D&D), for each NPP plant in each time-period of the scenario.

Unlike other simulation codes, INCAS' Generation costs model is not a mere input section of the code: an original calculation routine allows to derive the construction costs of a specific NPP on the basis of a "top-down" estimation approach. Considering that data records on construction costs for advanced PWR are not available, the cost of a specific NPP is estimated from a reference, first-of-a-kind PWR of a given size. For a given scenario, with its specific investment schedule in terms of site collocation of plants and construction timing, INCAS calculates construction costs of each successive NPP unit of the fleet, by applying corrective factors that account for economy of scale, learning efficiency, modularization effects, co-siting economies and design-related savings. INCAS' premise is that the cost of "n" NPP units is not equal to "n" times the cost of one NPP. Learning and co-siting economies are determined by the construction schedule and strategy, while design-based savings and modularization are related to the plant size.

In particular the code takes into account:

- learning economies, both at single site level and worldwide, with two different learning accumulation and decay laws;
- design modularization savings on construction costs;
- co-siting economies, due to fixed costs sharing by multiple units built and operated on the same site;
- economies of scale;
- design simplification and enhancements' impact on overnight construction costs.

Reference construction cost is therefore adjusted by mean of capital cost factors that account for the above-mentioned benefits, through suitable cost saving factors.

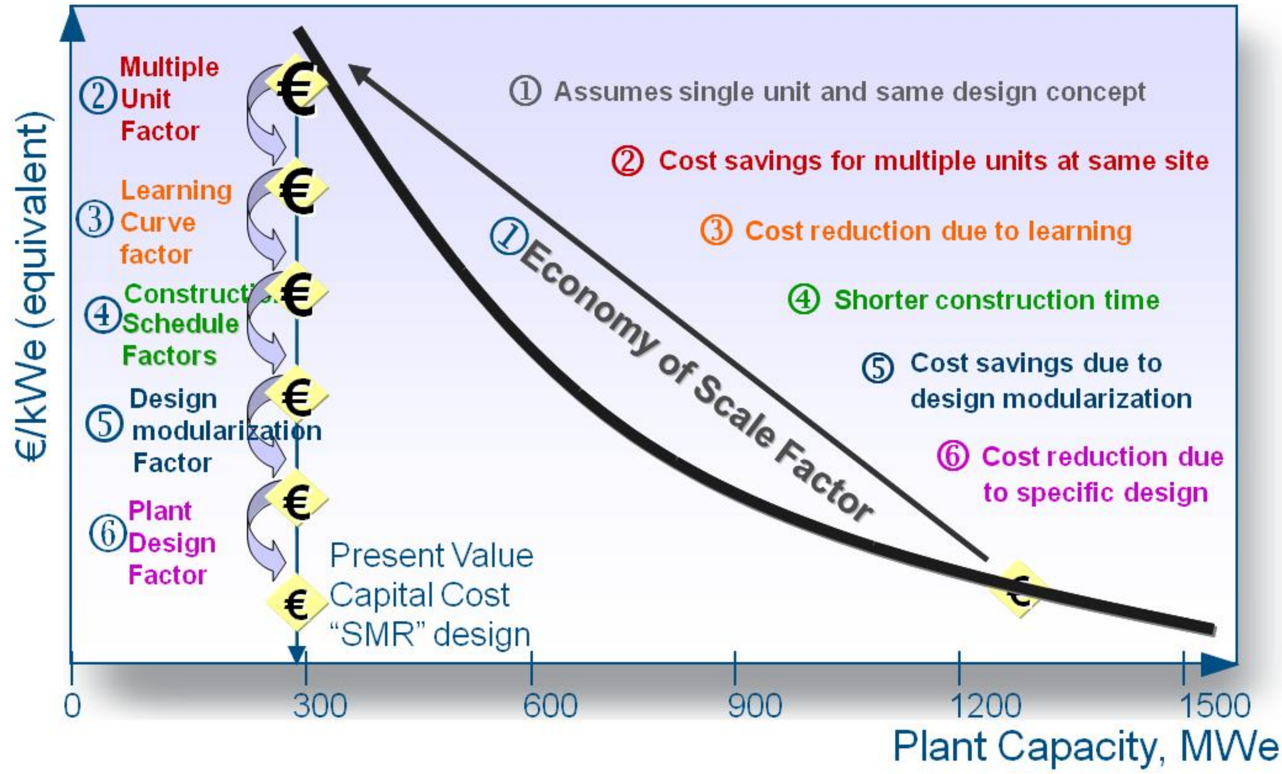

Fig.6 INCAS' top down estimation pattern for SMR overnight costs' estimation

All of the above mentioned cost factors have been modeled on the basis of open literature values and implemented in the INCAS code, with the exception of design saving factor. As said in par 3.1.1, such saving factor account for technology simplifications and enhancements made possible by lower plant size and have to be provided to the model on the basis of expert elicitation.

Specific parameters ϑ_i are calculated and applied to the construction cost of a reference LR in a way that the construction cost of a smaller size NPP is scaled from it, through the following equation:

$$\delta = \frac{OCC^C\left(S_{SMR}, N_{n,SMR}, N_{World,SMR}, M_{SMR}, D_{SMR}\right)}{OCC^C\left(S_{LR}, N_{n,LR}, N_{World,LR}, M_{LR}, D_{LR}\right)} = \vartheta_{ES} \times \vartheta_l \times \vartheta_{CS} \times \vartheta_M \times \vartheta_D \qquad (2)$$

where ϑ_{ES}, ϑ_l, ϑ_{CS}, ϑ_M and ϑ_D are the factors related to Economies of Scale, learning, co-siting, modularity and design features, respectively; OCC^C, S, N_n, N_{World}, M and D are the Overnight Construction Cost (€/kWe), the reactor size (MWe), the number of units of the same type built on the same site and built in the world, the degree of modularity and the innovative design solution feature, characterizing the power plant. The overall construction cost scaling factor δ for the SMR against the LR, is then obtained by multiplying the ϑ_i parameters.

By a special "Advanced" user-input section INCAS offers the user the option to intervene in the cost saving factors modelling, overriding the default settings with specific, proven information.

The overnight construction cost calculated as above, is spread over a construction schedule time period following a traditional "S-curve" for cumulated expenses.

Over this period, specific cost escalation rate is applied to overnight capital cost to account for specific inflation rate on the reactor plant construction inputs (i.e. structural materials, labour..), that might grow with annual rates different from general inflation, following specific price dynamics, usually correlated to the energy price.

Finally, construction schedule overruns are translated into cost overruns that grows linearly with time-delay.

Operation and Maintenance and fuel unit costs are given to the model as an input by the user. It might be assumed that O&M cost of different sized NPP are influenced by multiple-units economies, EOS and fuel cycle length and that fuel cost may differ depending on the enrichment level. A quantitative model of these costs will be offered by further development and refinement of INCAS code. D&D unit costs are inputed by the user as well and represent an annual cash outflow that increases a specific segregated fund. Available information on D&D expenses highlights a clear dependence on EOS and on multiple units factor. Nevertheless as of today a quantitative model for the estimation of this cost item is not provided by INCAS and will be included as well in the code's further development.

5.1.2 Revenue Model

The purpose of the Revenue Model is to forecast electricity demand and market prices in order to estimate future annual cash in-flows. Some of the elements that could enter into such a model are:

- The electric capacity already installed;
- The degree of competitiveness among the suppliers on the market;
- The mix of energy technologies for electricity production;
- The electrical grid structure and capability;
- The space-time trends of the demand for electricity;
- The adopted competitive strategy for new power plants.

The output of the revenue model are total revenues at the plant level over the economic plant lifetime, i.e., estimates of the total inward cash flows. The revenues R [Euro] are a function of the country- or local-level electricity consumption Q [MW(e)-hour], the market price p [Euro/MW(e)-

hour] or the market structure drivers MS^1, the plant size S [MW(e)], the specific reactor technology T (e.g., whether the reactor is a large reactor or a SMR), and a set Y of other variables:

(3) $$R = R(Q, p \text{ or } \mathrm{MS}, S, T, \mathrm{Y})$$

The Y inputs include the load factors, the national electrical grid and the front-end investments.

A detailed electricity market simulation model is beyond the scope of INCAS; this input information is necessarily country-dependent, in order to acknowledge the specific market structure and players (i.e. market pools, etc.).

Built as a modular model, INCAS may be interfaced with appropriate market model and use their output (i.e. long-term forecasted electricity price and power output demand) as an input for its elaboration.

In its stand-alone version, INCAS elaborates a simple, linear Revenue Model to feed the Investment Model.

5.1.3 Financial Model

The purpose of the financial model is to evaluate the cost of invested capital. For any project, weighted average cost of capital (WACC) could be calculated by means of the well known formula:

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

where the necessary inputs are:

- Equity amount (E) invested in the project;
- ratio of Debt to Equity (D/E) for the company, enterprise or organization's investment;
- rate of return required by shareholders for the equity (K_e), which is the cost of equity;
- interest rate required by debt holders (K_d);
- tax rate (t).

Because NPP projects with smaller reactors are generically more scalable[2] and reversible, they may allow for better investment timing and smaller capital outlays, resulting in lower project risk. This in turn, may account for lower debt interest rates and allow for higher use of financial leverage.

[1] MS include total installed capacity, reserve margin, supply mix, concentration indexes and market shares, spot power exchange versus long-term bilateral contracts, etc.

[2] With capacity and investments added in smaller increments.

Cost of capital also depends on the investment model, either project financing or corporate finance: in the first case cost of capital should represent the project specific financial risk, in the second case financial risk could be endorsed and mitigated by general credit rating of the investor and granted by its overall cash-inflow portfolio. Other things being equal, project financing is generally represented by higher capital cost than corporate finance and, without particular guaranties or contractual agreement able to reduce the project risk, it may simply be unviable. Such consideration have to be included in the cost of capital assumptions.

On the basis of the cost of capital and the financing mix, the DCF model accounts for the time value of money, calculating the Interest During Construction (IDC) on financial debt: IDC represent a relevant part of total capital investment. Interest expenses during construction period are capitalized in the amount of loan outstanding; thus, construction period is assumed to be a sort of "grace period" and IDC do not represent an actual cash outflow, but they are due to lenders and increase the debt stock amount. Actual interest payment starts with commercial operation of the plant.

5.2 Investment Model – data elaboration and output

The INCAS code is able to calculate the full set of accounting values for each reactor plant at each time-step: the accounting values are classified in the three main financial prospects indicated in the following table:

PROFIT&LOSS	CASH FLOW STATEMENT	BALANCE SHEET:
revenues O&M costs fuel costs D&D depreciation EBIT interest expenses interest earnings tax NET PROFIT	(-) EQUITY INVESTMENT (+) EBIT (+) DEPRECIATION (-) TAX (+) INTEREST EARNINGS (-) INTEREST EXPENSES (-) DEBT PRINCIPAL AMORTIZATION FREE CASH FLOWS	NET ASSETS CASH EQUITY DEBT

Tab.III Financial prospects elaborated by INCAS

Profit&Loss (P&L) and Cash Flow (CF) statements refer to the current period values, while Balance Sheet (BS) deals with cumulated stocks of values.

P&L considers costs and revenues that are of competence of current fiscal period, while Cash Flow statement considers actual and effective cash outflows and inflows

INCAS calculates the set of three financial statements (Profit & Loss statement, Cash Flow statement and Balance Sheet) at each NPP level; then, all the financial statements of the whole NPP fleet are consolidated to calculate global key financial indicators. Thus, these indicators are representative of the whole investment case:

- Internal Rate of Return
- Net Present Value
- LUEC
- PBT

Each of the above mentioned output will refer to the NPP fleet investment project as a whole.
Net Present Value is the sum of all cash out-flows and in-flows, discounted by an appropriate rate that represent the cost-opportunity of the capital employed. Thus NPV is a decreasing function of the discount rate. If a discount rate is set, the corresponding NPV is to be considered as the excess value earned above the capital remuneration represented by the discount rate itself.
It means that if a 10% discount rate is assumed and 100M€ NPV is calculated, the investment project is able to generate 100M€ on top of 10% remuneration rate on the investment costs.
As far as shareholders' NPV is considered, the cumulated value of all the free cash flows is actualized with the cost of equity and represents the excess value generated by the investment project on top of the remuneration set by the user as the "cost of equity".
An NPV = 0 does not mean that the investment is not profitable, but it means that the capital investment remuneration is exactly equal to the discount rate applied in the cash flow actualisation.
Internal Rate of Return (IRR) is the key parameter that measures an investment profitability and is defined as the discount rate that breaks even the NPV.
IRR is the discount rate that balance all actualised cash out-flows (capital investments, operating, financial costs…) and in-flows (revenues...) and represents the specific rate of return of the investment project. It means that if a 12% IRR is calculated, the project is able to generate a 12% remuneration on capital investment.
Similarly, Levelized Unit Electricity Cost (LUEC) is the electricity price that breaks even NPV calculation, meaning the minimum sale price that allow investors to recover their capital invested + a capital remuneration represented by the discount rate applied to the NPV calculation. Thus the LUEC is a function of the discount rate, with a positive correlation: the higher the capital investment remuneration required , the higher is the electricity sale price that allow to earn such remuneration.

IRR and LUEC are calculated iteratively as the discount rate and electricity sale price, respectively, that break even the *NPV* of the investment project:

(5)
$$NPV = 0 = \sum_t \frac{CF_t\left(ee_{price}\right)}{\left(1+IRR\right)^t}$$

(6)
$$NPV = 0 = \sum_t \frac{CF_t\left(LCOE\right)}{\left(1+K_e\right)^t}$$

where CF_t is the cash flow of year t, which is function of the electricity price ee_{price}, while K_e is the cost of capital (Equity).

In addition to the above mentioned indicators, INCAS provides information for an holistic investment financial appraisal, such as: capital at risk, capital structure ratios (e.g. Debt-to Equity, maximum debt outstanding, debt cover ratio, debt duration), cash flow profile, interest cover ratio, etc.

INCAS is particularly devoted to the assessment of the nuclear investment project risk and profitability, as a feasibility requirement for the nuclear investment. It is therefore conceived as a dynamic simulation tool to test the boundary conditions allowing to meet a target project profitability; LUEC is then calculated with respect to the scenario input settings. Sensitivity analysis may be performed on each input variable.

Moreover, the Investment Model's dynamic cash flow analysis is able to capture the "self-financing" feature, a financial phenomenon typical of modular investments. It represents the capability of the project to finance itself, by re-investing the cash inflows from the early deployed NPP's operations into the later NPP units' construction.

If any positive free cash flow exists for a NPP, after covering debt obligations, it is diverted to cash-deficit NPPs under construction, at an extent defined by the user (from 0% to 100%), the rest being earned as "shareholders' dividends". That gives the shareholders the option to reduce the up-front equity investment effort, re-investing self-generated equity resources in the project, at an appropriate IRR.

Self-financing may represent a relevant financing source for staggered, modular investments in multiple NPP, that makes a project financially affordable by investors with limited up-front investment capabilities.

5.3 Stochastic scenario simulation tool

INCAS Matlab code is currently based on a deterministic approach to data input and elaboration. In order to simulate stochastic investment scenarios, an Excel-based version of INCAS has been generated, which reproduces the same data processing rules of the Matlab code. Then Excel code is combined with @RISK5.5 software for Montecarlo simulation. Nevertheless, due to PC data processing constraints face to the complexity of calculations and iterations, the Excel version of INCAS is able to run a Montecarlo simulations in an acceptable time-frame on a single site scenario deployment only. To bypass this limitation the Matlab version of the code is being upgraded in order to account for stochastic distribution of input and run Montecarlo simulation on NPP fleet at multi-site level.

6 SCENARIO TEST CASES

6.1 Single site simulation: assumptions

Nuclear investment presents very high risk profile that relates to the exceptionally extended time horizon of the project and to possible changes in investment environment conditions during this time horizon. Cash flows expectation is potentially undermined by possible regulation changes, reactor operation underperformance, electricity market downturn. If risk allocation countermeasures are undertaken, a nuclear investment project may enhance its level of dependability for receipt by a bank, financial attractiveness hence global viability.

Investment environment conditions may play a relevant role in the investment economic performance. In particular public support may intervene to relieve financial pressure through financial backing of debt or tariff support mechanism, caps on D&D liabilities, etc. These support mechanism are sensitive in a liberalized market environment and more easily implemented in emerging market state-controlled economies.

The level of risk allocation and the main economic features of the energy market environment may affect in a significant way a nuclear investment. To investigate different scenario conditions for nuclear power plant deployment, simulation scenarios have been set related to a "Merchant" business case, based on the rules of the liberalised electricity and capital markets, and a "Supported" business case, where special risk-mitigation policies and conditions are set in place.

These scenarios case studies are defined and tested with INCAS, at single site level on a single LR or 4 equivalent SMR, with same total power output. These test cases allow to investigate the specific performances of LR and SMR under the two different economic scenario environments. The scenario key features are summarised in Table IV.

	Oilkiluoto3	South Texas Project	INCAS "Supported" business case	INCAS "Merchant" business case

Debt interest rate (K_d)	2.6%	5%	5%	7%
State guarantees	28% on total debt[I]	up to 80% of total construction cost[II]	up to 50% of total construction cost	no
Financing mix	20% equity 80% debt	20% equity 80% debt	20% equity 80% debt	50% equity 50% debt[4-6]
Market risk	long-term electricity sale contracts at fixed price[III]	89% of power output sold through long-term contracts	long-term electricity sale contracts	sale at spot price
Cost of equity capital (K_e)	0%	not disclosed	10%	15%
EPC type of contract	Turn-key	No	target price with incentives	on cost basis
Tax rate	0% (non-profit)	18 $/MWh tax credit on first 8y operation	30%	30%
Financing scheme	20% equity; 5% corporate financing; 75% project financing	Na	Project Financing	Corporate Financing

Tab.IV Financing data from case studies and for INCAS test cases.

I - € 610M export credit from French State-COFACE to TVO; € 100M by AB Svensk Exportkredit-SEK.
II - on bank loans, standby insurance for regulatory delays.
III - at cost-price basis, estimated to be less than 25 €/MWh.

The "Supported" case is derived from the analysis of two case studies: Olkiluoto3[7] in Finland and South Texas Project[8-11] in the USA.

Both deployments have been structured in project financing, with TVO electric utility being the special purpose vehicle of the NPP investment in Olkiluoto.

The Olkiluoto case study represents a non-profit power generation business case, where a shareholders' cooperative consortium will off-take the power output through long-term electricity sale contracts at cost-price.

This configuration is able to offset long-term market risk. Although capital remuneration and project profitability are not strictly required by shareholders in this business case, but mainly invested capital recovery, nevertheless they still represent key economic factors in the scope of the analysis, with nuclear electricity being either a production input for energy-intensive industry or an intermediate good to be sold to local municipalities by the shareholders.

In the South Texas Project, market risk mitigation and public guarantee on banks' loans allow for low capital costs.

In the "Supported" case, a target 10% shareholders' capital remuneration rate is assumed to justify a lower entrepreneurial business risk, while in the "Merchant" case the nuclear investment project is left to the laws of the free market of capital and power generation.

Hence both shareholders and lenders will require much higher capital remuneration to cover long-term business risk and banks will ask for tighter loan covenants.

This might increase, in turn, the probability of financial default, while decreasing shareholders' profitability to an extent that project financing scheme would not be viable.

For this reason the financing nuclear project in "Merchant" environment is assumed to be possible only through corporate financing, with nuclear business risk being diluted on a diversified business portfolio of shareholders and with shareholders' assets to guarantee bank loans.

On the basis of a recent study[12] assuming 8% interest rate on debt for "Merchant" case project financing, a conservative 7% interest rate on-balance sheet financing is assumed for INCAS test case, for corporates with less than 50% of nuclear power business.

As far as construction and operating costs are concerned, the assumptions for LR and SMRs deployment to be used in INCAS test cases are based on the latest literature reported in Table V.

Deployment schedule are illustrated in Figure 7 and 8, the financial data (Table IV) and the scenario data (Table IV) have been identified, the test cases involving alternative LR and SMRs investment projects are simulated with INCAS and compared.

To investigate the calculation output sensitivity, a parametric analysis has been carried out, with values ranging on a (-10%; +10%) basis with respect to base values.

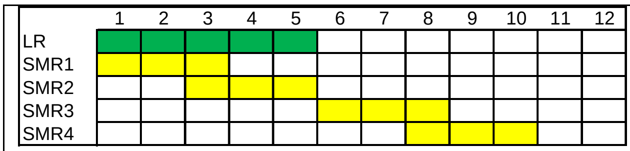

Fig. 7. LR and SMRs construction: SMRs "Short" deployment schedule – base case.

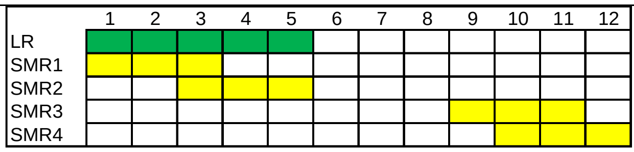

Fig. 8. LR and SMRs construction: SMRs "Long" deployment schedule.

Input	LR base value	SMRs base value	Rationale and Bibliographic ref.
Plant operating lifetime (years)	60	60	Same technology enhancement and reliability[19] assumed for LR and SMRs.
Estimated construction period (years)	5	3	LR total construction time considering the most common LR design installed worldwide.[23-28] Reduced construction time for deliberately SMRs due to reduced size and assuming design simplification [13-15].
Overnight construction cost ($/kWe)	4000	4284 (average)	LR value [12] assumed as conservative with respect to recent estimations [13, 16-20], while as optimistic with respect to recent contracts [21]. SMRs capital cost estimated from LR capital costs [3].
Operation and Maintenance cost ($/MWh)	9	10.8	LR cost assumed considering a deep investigation for US reactors [22] (conservative value since O&M cost for new NPP should be lower than previous generation reactors, due to design simplification and passive safety features [23]). SMRs O&M cost estimated from LR cost [24] (SMRs to LR ratio = 1.2x).
Fuel cycle cost ($/MWh)	6.7	6.7	Conservative estimation [4] assumed, as compared with other studies [5,6,25-28].
Decontamination & Decommissioning sinking fund ($/MWh)	3	5.9	A fee of 2 €/MWh is assumed as reasonable for LR, according to a thorough survey on decommissioning cost [29]. SMRs decommissioning cost estimated from LR cost [30,31] (SMRs to LR ratio = 2x).
Inflation (yearly %)	2%	2%	Average inflation rate for developed countries assumed [32].
Wholesale ee_{price} USA ($/MWh)	57.2	57.2	Average wholesale electricity price by NERC Region, 2001-2007 assumed [33].
Plant availability	93%	95%	Assumptions based on estimations for GenIII/GenIII+, LR [34] and SMR [35] examples.

Tab V Scenario reference data for INCAS test cases.

6.2 Country scenario simulation: assumptions

Multiple site scenario simulations have been run to assess economic performances of different NPP plant sizes. The same total power output is deployed by means of NPP fleets of different size:

- Very Large Reactors (VLR, 1500MWe)
- Large Reactors (LR, 1000MWe)
- Medium Reactors (MR, 350MWe)
- Small Reactors (SR, 150MWe)
- Very Small Reactors (VSR, 50MWe)

Total nominal power of 9GWe (8,100MWe generation capacity) is assumed to be deployed in 15 years on 3 sites, by mean of multiple NPP of different LWR sizes.

We consider a site maximum size of total 4,500MWe and a "small site" of 1,000MWe to represent the 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.

It has to be highlighted that 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. 9 and Fig. 10).

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.9 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.10 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. 11 and Fig. 12.

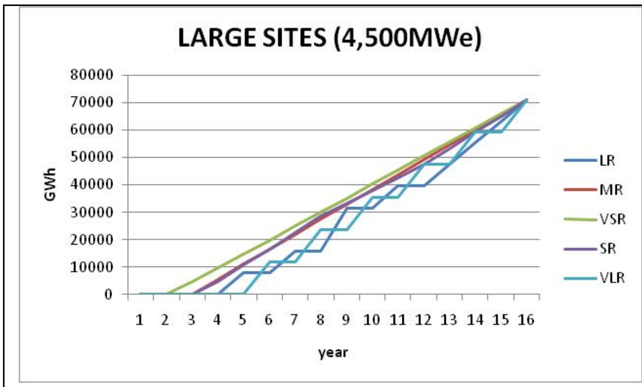

Fig. 11 Electric power installed rate on large sites (4,500MWe)

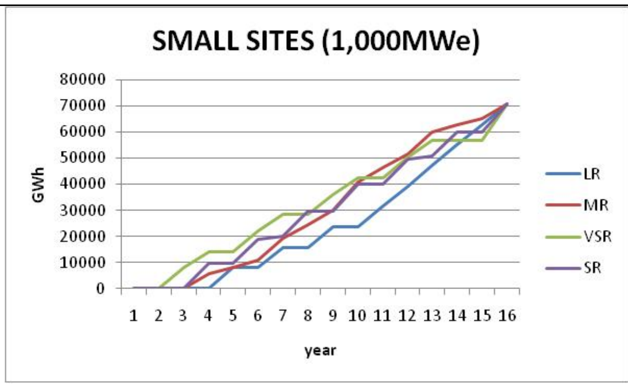

Fig. 12 Electric power installed rate on small sites (1,000MWe)

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 (par.5.1.1). Design saving factors have been considered as output results, in order to appreciate the target degree of design enhancement to put SMR economic performance in line with LR.

Assumptions on specific reactor data and on investment scenarios are summarized in Tab. VI and Tab. VII.

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

Tab VI Reactor-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

Tab VII Investment-specific assumptions

6.3 Stochastic scenario simulation: assumptions

Nuclear investments may represent a relevant industrial, economic and financial risk for investors, especially for those acting in liberalized markets of energy and capital. Main risks for industrial operators and merchant banks may be summarised in unpredictable cash flows over exceptionally extended project lifetime, on account of the lack of consolidated information and experience on both construction costs and operating performance and economics of new generation reactors.

Scenario conditions and input parameters to the economic evaluation of a nuclear investment project are affected by uncertainty.

Some of them are able to produce a relevant impact on project profitability. Among these most sensitive parameters, there are construction costs.

Construction costs may be heavily affected by delay in the construction period. Construction costs and time overruns are an upmost feared event that is able to undermine the investment financial performance. Wide literature [36;37] approaches the impact of such delays on the economics of nuclear investment; construction costs show a significant cost escalation during construction delay. The scale of the impact is particularly evident in Olkiluoto and in Flamanville projects [7;38;39].

Construction duration of successive SMR modules normally reduces on account of improved assembling, construction and supply chain practice: this is the effect of learning accumulation that is accounted by INCAS model's "learning" curve and applied to successive NPP units as a cost saving factor.

Longer construction schedule due to lack of learning in first units does not represent unexpected delay events, which deal more with external factors, independent from fabrication, logistic and assembling usual practice.

Delays may come from unexpected supply-chain drawbacks or unplanned intervention of Regulator or external events of political nature or even natural catastrophes.

In this simulation work the effects of unexpected delay on construction costs are analyzed.

The uncertainty over other relevant input variable is taken into account assuming suitable stochastic distribution of values between in a reasonable range.

Stochastic uncertainty of inputs combines randomly through a MonteCarlo simulation to produce stochastic distribution of output parameters (i.e. profitability indicators).

Results obtained from this simulation work are useful as considered on a stand-alone basis and also as indicators of a comparative performance of SMR and LR categories.

Interesting considerations may arise from the analysis of the output distribution, concerning the concept of investment risk.

If the expected value of profitability accounts for the financial performance of a nuclear investment, its distribution shape may be related to the risk for the investors of not meeting the expected profitability rate; in other word, the investment risk.

Input values to the INCAs model are summarized in the following Table VIII.

Unit overnight construction cost for LR is a key assumption due to its impact on economic performance indicators [40].

According to the more recent and conservative information [4;41;42], mean value of unit overnight cost for LR has been set at 3,000 €/kWe. It has been assumed a triangular distribution [43] as in Figure 13.

Costs for each SMR unit are scaled from this data, accounting for dis-economies of scale, modularization cost savings, site-related cost sharing by multiple units, design saving factor. The average overnight costs of the 4 SMR units (i.e. mean value) is higher than LR (Fig.14).

Plant type	LR	SMR			
Overnight unit investment cost [€/kWe]					
Distribution	Triangular	Derived from LR: INCAS calculation – top-down estimation			
Values (min – max; most likely)	(2000 – 4000; 3000)				
Operating and maintenance cost [€/MWh]					
Distribution	Uniform	120% vs. LR's			
Values (min - max; mean)	6.3 - 11.7; 9.0				
Fuel cycle cost [€/MWh]					
Distribution	Uniform	Same as LR's			
Values (min – max; mean)	4.7 - 8.6; 6.7				
Decontamination & Decommissioning provision [€/MWh]					
Distribution	Uniform	200% vs. LR's			
Values (min – max; mean)	1.4 – 2.6; 2				
Construction period: expected duration					
	LR	SMR1	SMR2	SMR3	SMR4
Values	24	12	12	12	12
Delay event during construction period					
Distribution	Discrete uniform				
Starting period (quarter since the beginning of scenario)	0;1;2;3;4;5;6;7;8;9;10;11;12;13;14;15;16;17;18;19;20;21;22;23;24 (from 0 until end of construction period of LR)				
Duration (number of quarters)	0;1;2;3;4;5;6;7;8;9;10;11;12 (from 0 to 3 years)				
Electricity price [€/MWh]					
Distribution	Triangular				
Values (min –max; most likely; mean)	50 – 90; 70; 70				
Years for debt-loan repayment					
Distribution	Uniform				
Values (min – max; mean)	12.5 – 17.5; 15				
Average interest rate for loan repayment					
Distribution	Uniform				
Values (min – max; mean)	6.0% - 8.0%; 7.0%				
Inflation = 2% Financing mix (Debt/Equity+Debt) = 50% Cost of Equity for PI and NPV calculation = 13% Tax rate = 30%					

Tab. VIII Input of stochastic scenario simulation

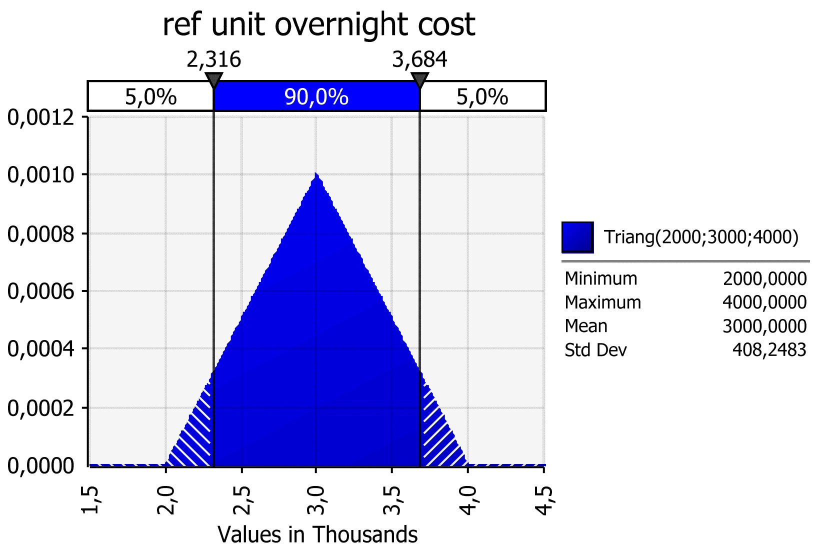

Fig.13 Unit overnight cost distribution of 1,000MWe LWR (€/kWe)

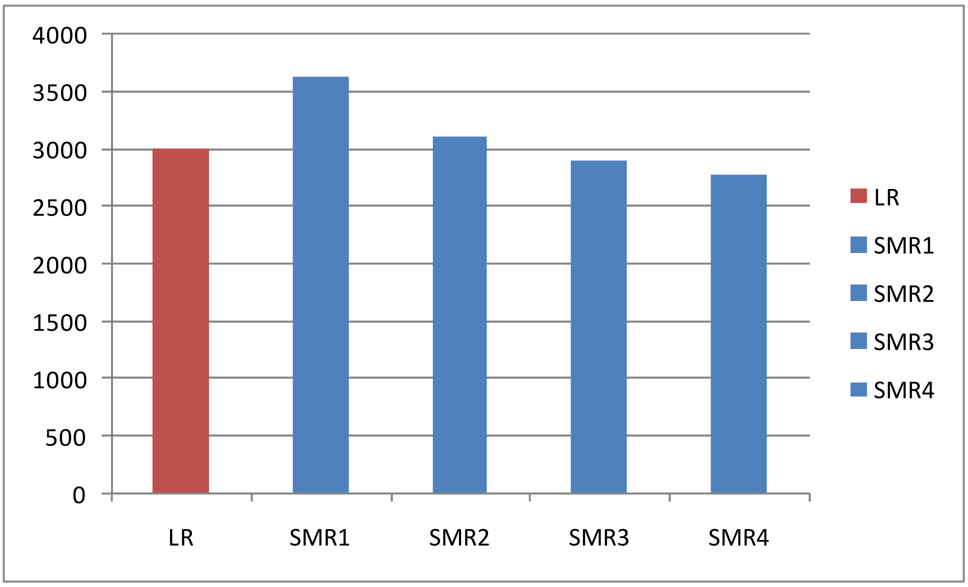

Fig.14 Unit overnight construction costs for LR and SMR (mean values; €/kWe)

At the purpose of studying delay impact on construction costs, it is considered that one of such delay events may happen randomly during the construction period.

This event produces a delay in the construction schedule of NPP affected and postpones NPP whose construction is not yet started until the end of the unfavorable event. For the purpose of simulation, such delay-event may take place during the construction period of LR (quarters from 0 to 24) and, whenever it starts, it affects one or more SMR units. As an example, Figure 15 shows a case where a 2-year delay-event starts in quarter n.10, thus prolonging the construction of SMR 1 and 2 (just started) and deferring the construction of SMR 2 and 4. Figure 16 shows a more severe case for

SMR, where delay starts in quarter 17 and jeopardize the construction schedule of SMR 1,2 and 3; SMR 4 construction is postponed until the end of the delay-event.

Given the modular nature of the SMR investment project and assuming staggered construction schedule, it is not possible that all SMR units are affected by the delay-event.

A priori, only a part of the SMR investment project will be vulnerable to the unexpected delay event.

YEAR	1				2				3				4				5				6				7			
quarter	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
LR	LR expected construction period																											
SMR1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SMR2	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
SMR3	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
SMR4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1

Fig. 15 Expected construction schedule of LR and SMR

YEAR	1				2				3				4				5				6				7				8			
quarter	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
LR	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SMR1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
SMR2	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
SMR3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
SMR4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0

Fig. 16 Construction schedule of LR and SMR with 2-year delay-event in quarters 10-17

YEAR	1				2				3				4				5				6				7				8				9			
quarter	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
LR	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1				
SMR1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SMR2	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
SMR3	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
SMR4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1

Fig. 17 Construction schedule of LR and SMR with 2-year delay-event in quarters 17-24

Due to the delay event, construction schedule of LR and SMR may last 6 to 9 years and 3 to 6 years respectively (4 to 7 years for 1^{st} SMR).

Literature demonstrates that planned and intentional delays' cost may be absorbed or accounted in the initial cost estimate; on the contrary, unexpected delay events always result in significant cost overruns, far beyond the initial cost estimates.

According to [36] a delay in the construction schedule produces 17.5% annual rate of increase in overnight construction costs (4.1% on a quarterly basis).

These values are consistent with Olkiluoto and Flamanville cost information.

Revenues depend on an electricity price distribution which ranges from a minimum of 50 to 100 €/MWh, with most likely value of 70 €/MWh.

The same plant capacity factor for LR and SMR is assumed, ranging from a minimum of 80% to 95%, with most likely value of 95% and mean at 95%.

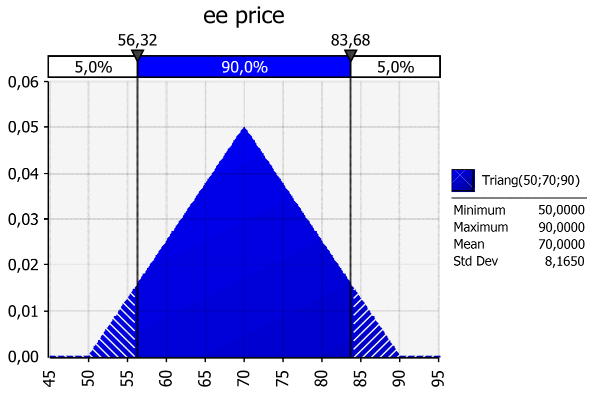

Fig.18 Electricity price distribution (€/MWh)

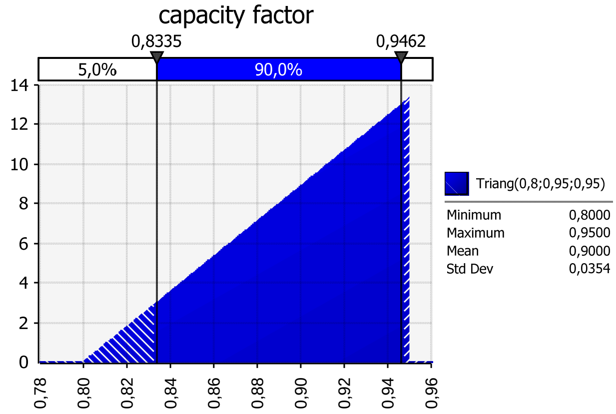

Fig.19 Plant capacity factor distribution of SMR and LR

The model is expressed in nominal terms and all costs and revenues increase with an annual inflation rate of 2%.

7 MAIN RESULTS

7.1 Single site simulation

LUEC of LR and SMR alternative investments has been calculated in "Supported" and "Merchant" business cases as the minimum electricity sale price that covers all the project life-cycle costs. In particular, LUEC allows for the invested capital remuneration on the basis of the cost of equity (K_e) and cost of debt (K_d): no extra-profit is left to shareholders on top of the cost of equity. Hence the cost of equity exactly equalizes the *IRR* of the free cash flows and represents the shareholders' capital remuneration.

As showed in Table IX, SMRs deployment has to set higher LUEC (+7% in the "Supported" case) to grant the same capital remuneration between LR and SMRs, on account of its higher construction costs. The calculation procedure sets the required capital remuneration (IRR) and considers the ee_{price} as an output: LUEC is the minimum sale ee_{price} needed to cover capital remuneration.

Case	"Supported" Case		"Merchant" Case	
Reactor size	LR	SMRs	LR	SMRs
LUEC ($/MWh)	55.0	59.1	96.1	96.3
Shareholders' capital remuneration	$K_e = IRR =$ 10%		$K_e = IRR =$ 15%	

Tab. IX key financial indicators for "Supported" and "Merchant" Cases

INCAS shows that SMRs deployment is less cost-effective than LR (higher LUEC) in the "Supported" case: lower power installed rate implies later revenues whose time value is penalised by actualisation.

The use of self-financing mitigates the up-front capital investment, but represents a higher recourse to equity funds, i.e. a more expensive capital source than debt, a less efficient financial leverage.

Moreover, the model is based on higher operating costs for SMRs than LR.

Nevertheless, as already mentioned, absolute value of output indicators has to be cautiously appreciated, given the high uncertainty on input data.

That means LUEC of SMRs and LR are substantially comparable, despite the loss of economies of scale on overnight cost for SMRs.

Moreover, the investment simulation of the two business cases highlights that SMRs are able to better cope with higher capital costs.

Fig. 20 shows the trend of LUEC as a measure of the economic performance of SMRs deployment, that improves on LR's with the cost of debt increasing.

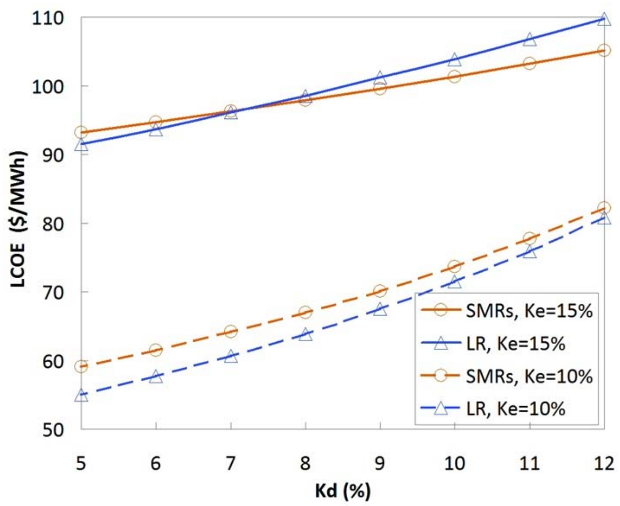

Fig. 20. LUEC trend at increasing cost of debt K_d, at different cost of equity K_e (i.e. for "Merchant" case – solid lines– and "Supported" case –dotted lines)

SMRs reveals to be a more suitable option to "Merchant" case's capital remuneration requirements: when financial leverage and/or cost of debt are higher, SMRs are able to limit interests capitalization and debt accumulation, due to shorter Pay Back Time for each NPP module.

Their financial behavior is more suitable and less sensitive to high cost of capital.

Table X itemizes the results related to the Overnight Construction Costs for the SMRs, according to the INCAS model and adopted in the simulation of the different deployment scenario.

	SMR #1	SMR #2	SMR #3	SMR #4	SMR average	LR
Economies of scale ($\square_{ES}$)	169%	169.3%	169.3%	169.3%	169.3%	100%
Learning ($\square_{l}$)	100%	92.5%	88.4%	85.6%	91.7%	100%
Co-siting economies ($\square_{CS}$)	100%	93.0%	90.6%	89.4%	93.2%	100%
Modularization ($\square_{M}$)	86.8%	86.8%	86.8%	86.8%	86.8%	100%
Design savings ($\square_{D}$)	85.0%	85.0%	85.0%	85.0%	85.0%	100%
Total combined cost factor (δ)	125%	107.5%	100.2%	95.7%	107.1%	100%
OCC ($/kWe) per reactor Unit	5000	4300	4006	3829	4284	4,000

Tab. X Overnight construction costs top-down estimation for SMR

The loss of economies of scale represents 69% construction cost increase on the first SMR module in terms of $/kWe, as compared to the LR. Nevertheless, the four SMRs units altogether gain cost effectiveness through the economies of multiples: the difference in LUEC is moderate if compared with the significant economies of scale penalty.

Learning accumulation in the construction phase reduces construction costs by nearly 8% on average over all the four SMRs (average cost saving factor is 91.7% on the four units with respect to the first one). Co-siting economies (i.e. fixed costs sharing) account for a further cost decrease of 7% on average. Total combined cost factor shows that construction costs of the third SMR (100.2%) are in line with LR's: as compared to LR, they decrease from +25% of first unit to +7% on average over all SMRs (4284 $/kWe with respect to 4000 $/kWe for LR).

Total capital investment includes not only the Overnight Construction Cost but also Interests During Construction (IDC).

INCAS model assumes a grace period for debt and interest payment, during construction phase, with interest expenses being capitalized, i.e. increasing debt outstanding. Table VI shows that overnight costs are 7% higher for SMRs than LR (+284 M$), but INCAS calculates lower *IDC* for SMRs than LR.

As an example, in the "Supported" case SMRs' *IDC* are 50% than LR's, with a net saving of -297 M$: as a consequence, Total Capital Investment Cost (*TCIC*) is only 83 M$ higher for SMRs than LR. The TCIC for LR and SMRs are fairly the same (5961 M$ and 6045 M$, respectively).

That is argued by the shorter construction time for each SMR and the consequent shorter investment Pay Back Time, accounting for limited interest capitalization during the construction period. SMRs are able to better control and limit the financial debt accumulation during the construction phase. By increasing the cost of debt K_d from 5% to 7% in the "Supported" case, all the rest being equal, *IDC* will increase from 10% to 14% of *TCIC* for LR, while SMRs' *IDC* will only increase from 5% to 7%.

Construction scalability offers the investors the option to concentrate or dilute the power installed rate through the construction schedule of multiple NPP units. Staggered construction of multiple NPPs generates free cash flows from the operation of early units, that can be re-invested in the same project at the IRR profitability rate. It represent a self-generated equity financial resource able to contain the up-front equity investment. The higher the revenues (i.e. ee_{price}), the higher is the self-financing source because shorter is the Pay Back Time for the early units.

This option is not available to the single monolithic LR and. At minimum ee_{price} conditions, it allows to limit the up-front capital outlay (Equity+Debt) below that needed by the LR, as shown in Fig. 21.

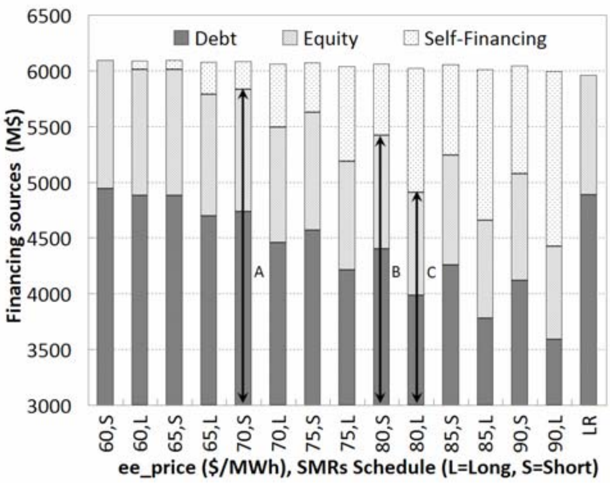

Fig. 21. Financing sources (Debt, Equity, Self-Financing) at different ee_{price} and SMRs deployment schedule – "Supported" case.

Self-financing generation may be fostered by diluting SMRs construction schedule over a longer period of time. With ee_{price} above 70 $/MWh, Debt+Equity investment needed to build four SMRs is lower than for LR, due to self-financing contribution (Fig. 21, "A"). With ee_{price} at 80 $/MWh, self-financing represents 11% of SMRs' TCIC: in the base case, i.e. 10 years construction schedule ("Short" deployment schedule, Fig.8), self-financing accounts for 641 M$ on total 6063 M$ TCIC (Fig. 21, "B"). If deployment of SMRs is re-scheduled over 12 years in a way that the first 2 modules work as "cash provider" to finance the construction of the last 2 units, then self-financing accounts for 19% (1115 M$) of TCIC (Fig. 21, "C").

With "Long" deployment schedule and 90 $/MWh ee_{price}, self-financing accounts for 26% of SMRs' TCIC (1571 M$).

It has been already shown that, given the same capital remuneration (K_e = IRR), SMRs are slightly less cost-effective (higher LUEC) than LR. Should the ee_{price} be higher than LUEC, as in the case of a free floating price according to electricity market and in growing economies, hence assuming growing electricity demand, lower cost-effectiveness translates in lower IRR for SMRs as compared to LR, given the same ee_{price}. This is shown in Fig. 22, where profitability curve of SMRs is lower than LR's at different ee_{price}.

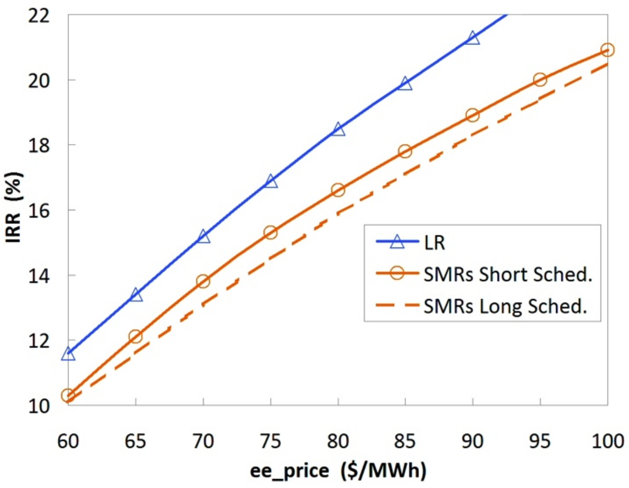

Fig. 22. Project profitability (IRR) with different ee_{price} and construction schedule – "Supported" case.

Fig. 22 also shows that longer deployment schedule is characterized by lower project profitability. Higher self-financing may reduce the up-front capital investment in terms of Debt and Equity under LR's, but it slightly reduces project profitability, due to revenues shift onward.

Moreover, recourse to self-financing reduces the up-front capital disboursement and the interests during construction over banks' loans, notwithstanding it represents an equity capital source, with higher cost as compared to bank loans.

A trade-off evidentiates between self-financing and profitability maximisation, assuming the latter is simply synthesised by the IRR parameter: the suitable deployment size and schedule have to be defined according to the strategic goals and financial and economic constraints of shareholders. It is also dependent from the shareholders business and investment structure (e.g. for-profit corporate, no-profit consortium of utilities and industries as in the Olkiluoto3 case, or sensible country's government involvement). Nevertheless, investment scalability offers an additional strategic option and flexibility.

Project risk has been investigated as the elasticity of project profitability with respect to a change in the scenario conditions.

The main results are summarized in Fig. 23 showing the input parameters with the highest influence on the project economic performance, with reference to the "Merchant" case. The same behaviour of the project profitability applies in the "Supported" case sensitivity analysis.

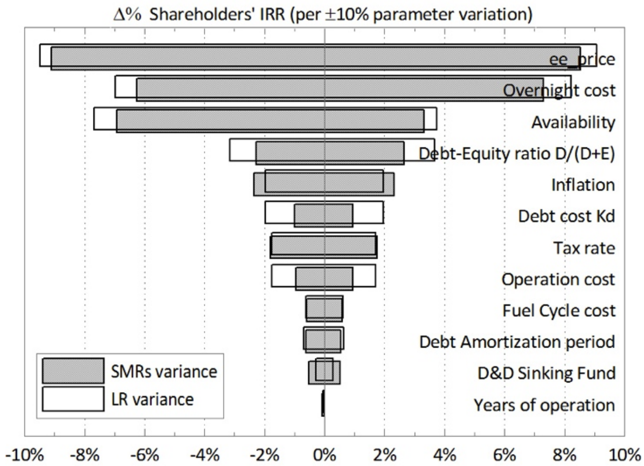

Fig. 23. Sensitivity of project profitability (IRR) to main parameter input data variation – "Merchant" case.

The IRR variation is assessed as a percentage of its base value (K_e=15%), according to a ±10% change in the input parameters (except for the NPP Availability, bounded to +5% in increase side, due to already high base values). The ee_{price} is left free to float according to electricity market price dynamics and assumed as an input to calculate the capital remuneration (IRR).

For almost all the parameters and business case, the sensitivity of LR's profitability is wider than SMRs': this indicates a lower financial risk for SMRs as a general trend. In particular, SMRs tend to better cope with cost of capital increase, higher financial leverage (Debt to Equity ratio, $D/(D+E)$) and higher construction costs.

Revenues, i.e. electricity price and plant availability parameters, are the main source of variation in project profitability, e.g. a 10% increase/decrease in ee_{price} can increase/decrease *IRR* by a 10% of its base value, i.e. roughly 1% in absolute value.

Capital cost has a strong influence on the investment profitability. It is incurred in the early years, when the time-value of money is higher, and represents a huge percentage of the life cycle cost.

Financial parameters (e.g. inflation, K_d, $D/(D+E)$) are more relevant than the operating costs (O&M, Fuel, D&D). The effect of a change in the latter on IRR is negligible.

Due to the staggered construction of SMRs over a longer time-period, SMRs are more sensitive to inflation, that accounts for an escalation in construction costs.

In general, sensitivity analysis shows a moderate trend of better financial suitability of the SMRs to face changed scenario conditions, with lower variability of project profitability as compared to LR.

Moreover, the outcome suggests that by securing the power output and electricity price with long term sale contract, if allowed by market rules in liberalised electricity markets, it is possible to off-set a relevant source of profit volatility. The introduction of a "price floor" (i.e. a minimum electricity price) cuts the negative tail of the electricity distribution reducing the risk for investors.

7.2 Country scenario simulation

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.

As a first result simulations show that, due to EOS, for a given specific value of overnight costs, investment profitability decrease with reactor size. The slope of the curves shows how critical is the assumption about overnight construction costs, whose unexpected overrun may undermine the overall investment performance.

Another interesting result is that for specific overnight construction costs under the threshold of 3,500€/kWe, investment profitability may be in excess of 14% for all NPP categories, with the highest profitability for VLR at 16%. Anyway, the gap between profitability curves shows that, given our scenario assumptions, Economy of Multiples alone is not able to overcome the loss of Economy of Scale for smaller plants, without any design related enhancements and further cost saving. The EOS impact on investment performance clearly increase its incidence with overnight cost increase.

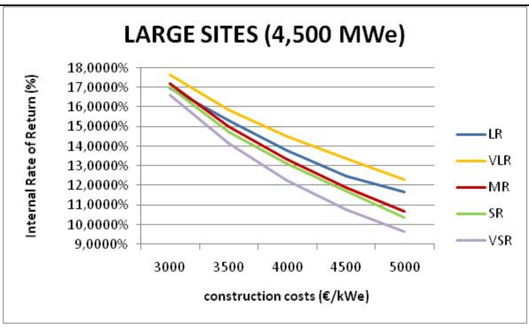

Fig. 24. Investment profitability with large sites and different sized NPP fleets

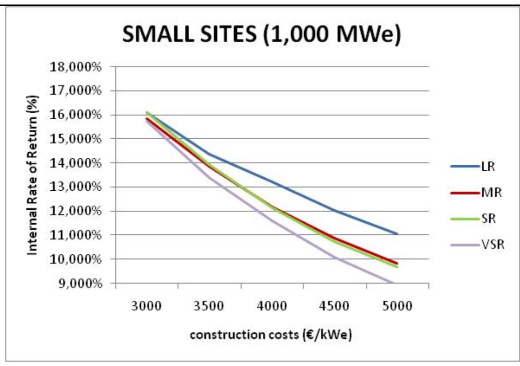

Fig. 25. Investment profitability with small sites and different sized NPP fleets

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. 1). 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 (Fig. 4), despite of even higher cost savings from modularization.

Different investment profitability is reflected in cost-effectiveness of each reactor fleet accordingly, as represented by LUEC (Fig. 26 and 27). LUEC is in the range of 90€/MWh, which means that, given our conservative assumptions, if electricity may be sold at least at LUEC value, investors are able to gain 15% profitability from their investment project. Clearly, would the target profitability expectation be lower than 15%, LUEC would also be lower than 90€/MWh.

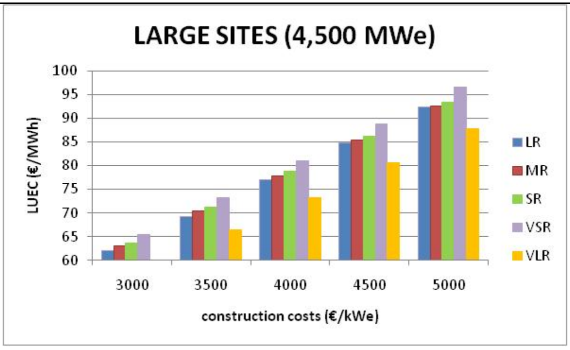

Fig. 26. LUEC with large sites and different sized NPP fleets

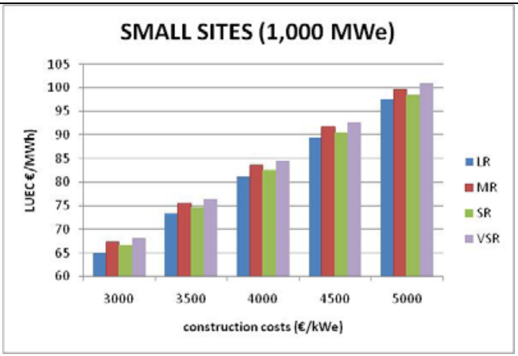

Fig. 27. LUEC with small sites and different sized NPP fleets

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. 27) 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. 25).

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. 28 and Fig. 29 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.

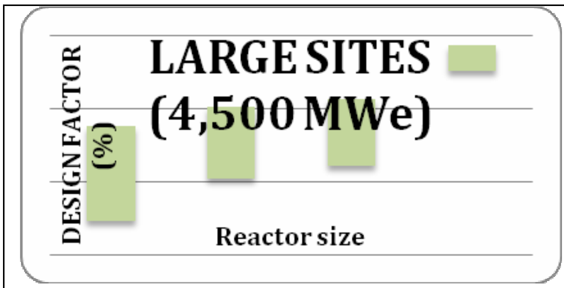

Fig. 28 Design saving factor ranges for different NPP fleets with large sites

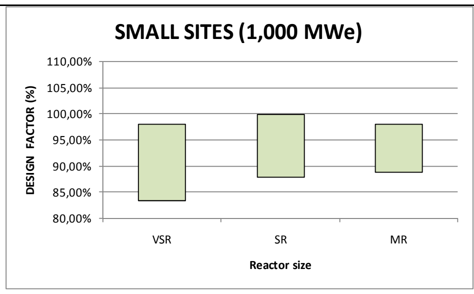

Fig. 29 Design saving factor ranges for different NPP fleets with small sites

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. 28). 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. 29). 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. 29).

Economy of Multiples capital cost factors (i.e. Modularization, Learning, Multiple units saving factors) represent a very sensitive input parameter in the comparative evaluation of LR and SMR, as is the Economy of scale factor. Their modeling deserves a sensitivity analysis.

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, 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. 30 and Fig. 31 show that VLR, LR and MR are more robust to cost saving factors variations.

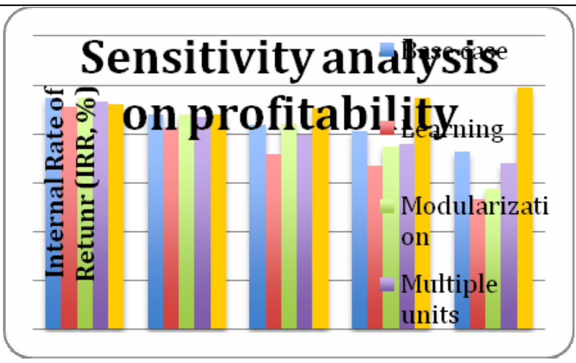	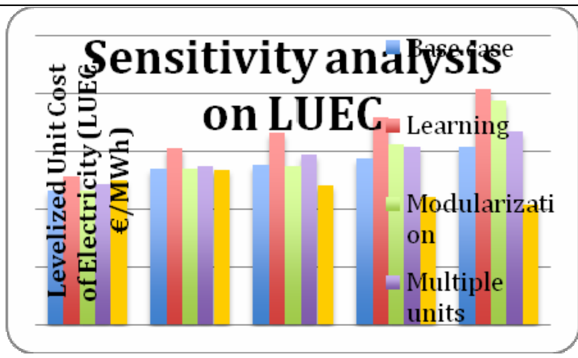
Fig. 30 Large sites scenario: IRR sensitivity to capital cost factors (overnight construction cost for	*Fig. 31 Large sites scenario: LUEC sensitivity to capital cost factors (overnight construction cost for*

reference 1,000MWe LWR = 4,000€/kWe)	*reference 1,000MWe LWR = 4,000€/kWe)*

7.3 Stochastic scenario simulation

SMR and LR projects represent two physically different systems, due to the different rate of power installed: Economy of Multiples generates its benefits with staggered deployment of successive units.

The scale of the investment is also different, due to the different overnight construction costs and the different IDC: TCIC is 3,524 and 3,392M€ for LR and SMR respectively.

Total Capital Investment Cost are defined as the sum of capital expenditures (including cost escalation due to delay on construction schedule) and financial expenses during construction period (Interests During Construction).

Higher unit overnight costs of SMR account for higher capital expenditures (Tab.XI), but this figure is compensated by lower IDC [44].

SMR shorter lead times allow for shorter Pay Back Time for each NPP unit.

Financial loans may be contained more efficiently and interest expenses capitalization as well. Moreover, cash flow from operation of early deployed units may be invested in the construction of later units, as investment "self-financing".

The difference in TCIC is even more evident in stochastic scenario: mean value of TCIC is 3,999 and 3,581M€ for LR and SMR respectively.

Despite higher unit overnight cost for SMR, capital expenditures are lower due to lower impact of delay event on cost escalation: SMR project is only partially affected because of staggered construction of SMR. Mean value of SMR IDC is about 50% of LR's.

	Deterministic scenario		Stochastic scenario	
	LR	SMR	LR	SMR
TCIC (min ; max)	3,524	3,392	3,999 (2,707 ; 2,425)	3,581 (2,288 ; 5,603)
of which:				
Capex [M€] *(min ; max)*	*3,157*	*3,202*	*3,484* *(2,077 ; 6,649)*	*3,336* *(2,130 ; 5,178)*
IDC [M€] *(min ; max)*	*368*	*189*	*515* *(162 ; 1,121)*	*245* *(111 ; 597)*

Tab.XI TCIC, Capex and IDC of LR and SMR in deterministic and stochastic scenarios

Given the different scale of investment and time horizon, Profitability Index is a suitable adimensional and synthetic indicator of the financial performance of the two alternative investment projects.

Deterministic scenario results show the superiority of LR with 1.31 % PI; the whole SMR project records no more than 1.23%. In terms of monetary value, given the scale of these investments, the difference in PI translates in 105M€ difference between higher LR's NPV and SMR's.

Nevertheless, when input uncertainty is included in the analysis, Montecarlo simulation on 10.000 stochastic scenarios produces lower PI of LR than SMR's, in terms of mean values of related distributions. Unfavorable scenarios are able to undermine LR profitability more than SMRs'. Standard deviation of SMR PI is higher than LR's meaning that longer right tails are possible: max PI is 2.90 and 2.36 for SMR and LR respectively. This means that SMR have greater chances to perform better as compared to the mean profitability than LR.

Skewness of PI distribution is higher for SMR than LR: 0.55 and 0.45 respectively, meaning that results for SMR are more dispersed toward positive values higher than the mean: this is evident in Figure 32 and 33. Kurtosis of SMR's PI is higher than LR's indicating a more picked distribution of results. When profitability distribution is not symmetric, variance cannot represent an indicator of business risk.

Of course, the more spread is PI the more uncertain is the investment return and uncertainty about return means "risk", but since the PI values are spread toward right positive tail beyond LR's maximum, PI variance alone is not sufficient to evaluate business risk. Conclusions must be based on comprehensive information about the shape of PI distribution.

NPV shows the same behavior as PI, with stochastic mean value for SMR higher than LR's: 97 and 40M€ respectively and a broader range of variation for SMR's NPV towards positive values (right tail): minimum NPV is almost the same for LR and SMR, while max NPV is significantly higher for SMR.

	Deterministic scenario		Stochastic scenario	
	LR	SMR	LR	SMR
PI [%] (min ; max)	1.31	1.23	1.06 (0.23 ; 2.36)	1.12 0.17 ; 2.90
Std deviation of PI	-	-	0.29	0.37
NPV [M€] (min ; max)	362.9	257.8	39.9 (-1,283 ; 1,187)	97.1 (-1,266 ; 1,361)
Std deviation of NPV	-	-	325.8	386.1

Tab.XII PI and NPV of LR and SMR in deterministic and stochastic scenarios

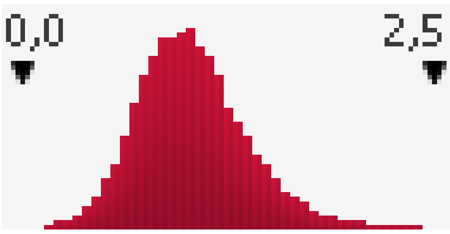

Fig. 32 Distribution of PI of LR

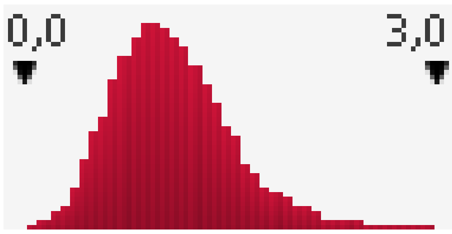

Fig.33 Distribution of PI of 4 SMR

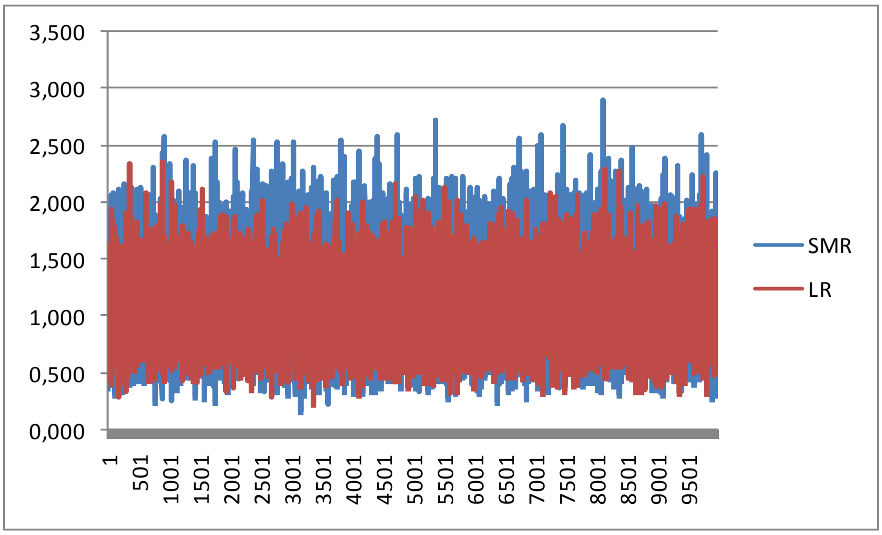

Fig.34 PI of LR and SMR: 10,000 Montecarlo simulations

The loss of value from deterministic to stochastic scenario is higher for LR: 323.0M€ versus 160.7M€. LR project is more exposed to uncertainty, while SMR project seems more able to absorb unfavorable scenario conditions.

8 CONCLUSIONS

The single site scenario simulation highlights interesting features of "modular investment". Multiple SMR represent an investment paradigm alternative to monolithic LR, with the economic benefits of the "Economy of Multiples".

The benefits of this paradigm are evident in the case study where four SMRs are considered against a single, monolithic LR, on account of their intrinsic investment scalability.

INCAS shows that a "modular" investment project in multiple SMRs power blocks may be able to off-set most of the loss of economies of scale. Then, in the range of uncertainty that affects the model's inputs, LR and SMRs record a substantially comparable cost-effectiveness.

SMRs are a suitable option in "Merchant" case scenarios, with limited financing costs escalation and financial risk (i.e. profitability variance). DCF dynamic model highlights the advantages of self-financing in multiple SMR, that together with the option to stagger the units' deployment schedule, makes SMRs an affordable option for investors with limited financing capabilities and a chance to contain the average capital exposure. LR, as their counterpart, grant a better economic performance in "Supported" scenarios, where market conditions are less volatile and where overnight construction costs have higher incidence on total capital costs, including financing costs.

LR and SMRs are the answers to different market conditions and investors' goals: LR's economy of scale is more relevant as a competitive edge where scenario conditions are more predictable, while SMRs appear to be more suitable as an option to control financial risk and limit up-front investment and average capital at risk.

INCAS simulations allowed to understand what are the key input parameters that may affect the economic performance of the nuclear investment. They confirmed the relevant incidence of capital costs on the economic performance of a nuclear investment project.

Further investigations on a multi-site, country level have been undertaken to contribute to the study of the economics of an investment in a NPP fleet and of the 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 even at multi-site level, Economy of Multiples is able to compensate the loss of EOS of SMR, when construction costs are assumed in their lower bound estimation. Nevertheless, as the assumptions on construction costs become more conservative, further design efficiencies are needed to bring additional cost-competitiveness to smaller NPP. Medium Reactors and Small Reactors (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 change the economic model's assumptions about construction cost saving factors, 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 then focused on the advantages of modular investment in smaller NPP, not only from the mere cost-effectiveness point of view, but even in the investment risk perspective, in order to catch a more complete picture of the economic performance of different NPP categories.

Uncertain scenario conditions have been tested on a single LR compared to 4 SMR with the same power output in a single site Montecarlo simulation. Input variables have been set in line with conservative, "merchant" market conditions as far as mean value are considered.

Nuclear business risk derive from:

- capital intensive nature with huge sunk costs and high financial exposure during very long Pay Back Times.
- Very long time forecasts reliability.

- Unexpected, external unfavorable events that constitute severe drawbacks to the project economics, such as construction time and cost overruns.

Nuclear investment concerns very long time horizon and input data introduce great dispersion to account for great uncertainty of long term forecast capability.

One of the main concerns for investors is unexpected delay during construction of NPP and related cost escalation. Face to the above mentioned risks, several investors stand "frozen" before the risk of "betting their company" on mistaken forecasts.

Investment in liberalized electricity markets compel investors to include uncertainty in their business plan analysis and to give risk as much relevance as profitability into their decision making.

All this considered, this work aims to contribute to the research by providing a deeper outlook of how uncertainty affects nuclear investment.

In particular, results on LR and SMR's behavior in stochastic scenario analysis allows interesting considerations:

- Exploiting investment scalability and shorter lead times, multiple SMRs are able to dilute and contain the capital investment and to self-finance the construction of later units with operating cash flow from early deployed units. The whole SMR project shows lower mean TCIC than LR, despite higher unit overnight costs and much lower IDC than LR. This reduces sunk costs and investment risk of SMRs under uncertain market conditions and this is a valuable option in a "merchant" scenarios where business profitability is as relevant as business risk [5].

- The lower financial exposure gives the multiple SMR system more financial stability face to unfavourable boundary conditions: lower average invested capital accounts for lower interests capitalization and lower risk of financial default.

- The above mentioned feature gives SMR the capability to better absorb cost escalation triggered by delay in the construction schedule. Due to staggered construction schedule, multiple SMR appear less exposed to delay events and confirm to be more able to cope with this kind of unfavorable scenarios.

When deterministic scenario are considered, LR shows its superior economic performance based on economy of scale and lower overnight construction costs: static values confirm the better financial performance of LR (e.g. PI).

When scenario conditions become stochastic and uncertainty is included in the analysis, then results are reversed: multiple SMR record higher mean PI, with more favorable data dispersion toward positive values in right tails.

Thus, Montecarlo scenario simulations show that multiple SMR represent a "modular" investment concept that is more able to absorb unfavorable scenario conditions than monolithic LR. On account of their competitiveness with LR in terms of project profitability and on account of their better performance to scenario uncertainty, they may represent a valuable alternative option, not only in small developing areas, but also for adding or replacing nuclear power plants installed in mature and liberalized large markets.

Nevertheless, SMR face other inconvenient among investors: new SMR are seen as "first of a kind" due to lack of commercial experience of new evolutive designs: this implies FOAK engineering costs, regulatory acceptance risks, first investor mover reluctance, etc.

9 GLOSSARY

DCF = Discounted Cash Flow

D&D = Decontamination and Decommissioning

EOS = Economy Of Scale

IDC = Interests During Construction

IRR = Internal Rate of Return

K_e = cost of equity

K_d = cost of debt

LR = Large Reactor

LUEC = Levelized Unit Electricity Cost

LWR = Light Water Reactor

MFA = Mass Flow Analysis

MR = Medium Reactor

NPP = Nuclear Power Plant

NPV = Net Present Value

OCC = Overnight Construction Cost

O&M = Operation and Maintenance

PBT = Pay Back Time

PI = Profitability Index

PWR = Pressurized Water Reactor

SMR = Small-Medium Reactor

SR = Small Reactor

TCIC = Total Capital Investment Cost

VLR = Very Large Reactor

VSR = Very Small Reactor

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