FINANCIAL CASE STUDIES ON SMALL- AND MEDIUM-SIZE MODULAR REACTORS

FUEL CYCLE AND MANAGEMENT

KEYWORDS: *small-medium size, modular reactors, economics deployment scenario*

SARA BOARIN,[a]* GIORGIO LOCATELLI,[b] MAURO MANCINI,[b] and
MARCO E. RICOTTI[a]

[a]*Politecnico di Milano, Department of Energy, CeSNEF-Nuclear Engineering Division,*
Via La Masa, 34, 20156 Milano, Italy
[b]*Politecnico di Milano, Department of Management, Economics & Industrial*
Engineering, Via Lambruschini, 4/B, 20156 Milano, Italy

Received August 31, 2010
Accepted for Publication January 5, 2011

Nowadays interest in small- to medium-size modular reactors (SMRs) is growing in several countries, including those economically and infrastructurally developed. Such reactors are also called "deliberately small reactors" since the reduced size is exploited from the design phase to reach valuable benefits in safety, operational flexibility, and economics. A rough evaluation based only on the economies of scale could label these reactors as economically unattractive, but that approach is incomplete and misleading. An economic model (INCAS—INtegrated model for the Competitiveness Assessment of SMRs) is currently being developed by Politecnico di Milano university within an international effort on SMR competitiveness fostered by the International Atomic Energy Agency, suitable to compare the economic performance of SMRs with respect to large reactors (LRs). INCAS performs an investment project simulation and assessment of SMR and LR deployment scenarios, providing monetary indicators (e.g., internal rate of return, levelized cost of electricity, total equity employed) and nonmonetary indicators (e.g., design robustness, required spinning reserve).

This paper presents the general features and purpose of the INCAS model, detailing the input required, and points out the main differences with other simulation codes. INCAS is applied to evaluate the financial attractiveness of an investment in four SMRs with respect to a single LR with the same power generation capacity installed, in different deployment scenarios. Then, a sensitivity analysis highlights the degree of elasticity of the key output parameters for the investors, with respect to the most sensitive input parameters.

Given the uncertainties of the main input parameters, INCAS results are affected by uncertainties as well. However, the financial output parameters provide a general understanding on the investment economics: INCAS shows that the economy of scale is not the only cost driver, because the economies of multiples may compensate for most of the gap in the economic performance of the SMRs. The uncertainties that affect the input data and the model do not allow declaration of a straightforward and neat economic performance superiority of SMRs versus LRs, or vice versa. Nevertheless, some trends have been highlighted. In particular, in "supported" market scenarios, where overnight construction costs have the highest incidence and the market conditions are less volatile, the most suitable strategy is to pursue the economies of scale. In contrast, SMRs behave better in "merchant" scenarios, where the cost of financing is higher and financial risk is sensitive. A "modular" investing strategy with a step-by-step power block deployment process allows lower financial exposure and less capital at risk and may mitigate the impact of scenario uncertainties on a project's profitability.

---

*E-mail: sara.boarin@polimi.it

I. INTRODUCTION

In the framework of a renewed interest in 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 decades in the United States 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 and to the decay of experience in plant construction, questionably balanced by the technological advancements in reactor design.

Moreover, small- to medium-size modular reactors (SMRs) have come to the scene,[1–7] where plants' size maximization has been pursued by the nuclear industry since its beginning. The loss of economies of scale seems to be undermining the economic competitiveness of such designs; however, the size reduction can be balanced[8,9] by other advantages, e.g., in financial risk, fabrication and transportation of the equipment, construction, safety, and grid stability.

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, which are hardly predictable because 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 prior step to the investment decision; project simulation may contribute to understanding the boundary conditions that make a project affordable and profitable from an economic point of view.

Several codes are increasingly used today for assessment studies, including some economic features, as reported in Table I (Ref. 10). 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 dynamic mass flow analysis (MFA) simulation. Their capabilities in facing nonstandard 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, indeed cover a comprehensive set of applications. Some tools devoted to market simulation, supported by the International Atomic Energy Agency (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 modeling tools are specifically intended to address various areas, such as safety, environmental (e.g., SIMPACTS), proliferation resistance, or 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 modeling and simulation of power generation investment projects. Among the latter, most of the available codes are traditionally focused on generation costs, with levelized cost of electricity being the main output and economic indicator.

Only a few codes [DANESS (Ref. 11), FINPLAN (Ref. 12), and INCAS (Ref. 13)] involve a dynamic cash flow analysis.

In this framework, INCAS (INtegrated model for the Competitiveness Assessment of SMRs) has been conceived as a simulation tool, able to evaluate the key economic performance indicators of a nuclear investment scenario at a single site or at multiple sites, at a country level.

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 as compared to large reactors (LRs).

Besides the description of the INCAS model architecture, two test cases are analyzed and described in the paper:

1. a "merchant" business case, based on the rules of the liberalized electricity and capital markets
2. a "supported" business case, referred, for example, to special risk-mitigation policies and conditions.

Each simulation case is run involving alternative LR and SMR investment projects and the results are discussed and compared. A sensitivity analysis investigates the project risk, intended as the elasticity of key economic performance indicators to changed scenario conditions. Moreover, to exploit the flexibility in the construction timing, different construction schedules for multiple SMRs are simulated.

II. INCAS MODEL ARCHITECTURE

The general architecture and development strategy of the INCAS code is summarized in Fig. 1. The investment model is based on a discounted cash flow model and provides the indicators of the investment's financial performance (e.g., internal rate of return, net present value,

TABLE I

Synopsis of Integrated Nuclear Energy Systems Simulation Codes

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

TABLE II

Main Features of the Economic Simulation Codes

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

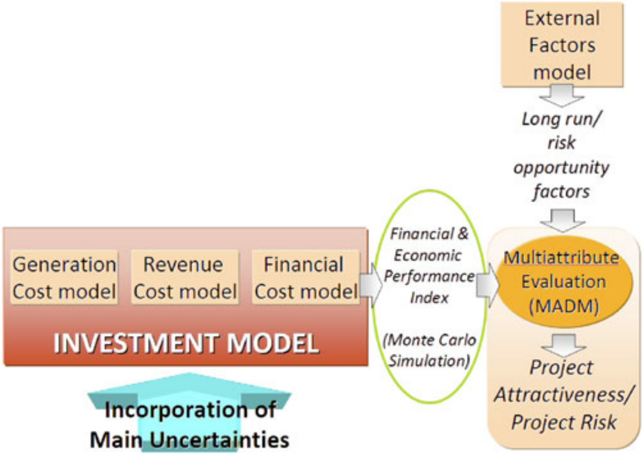


Fig. 1. The INCAS model architecture.

cash flow profile). 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. The financial and external factors models' outputs are then combined through a multiattribute evaluation process.

This paper deals with an application of the investment model to alternative investment projects in nuclear power: The economic performance of LRs and SMRs is analyzed and the results are compared on the basis of a set of key financial indicators.

The investment model includes the following modules:

1. generation costs [construction and operating costs, including operation and maintenance (O&M), fuel cycle, and decontamination and decommissioning (D&D)]
2. revenues (plant's availability, electricity sale price)
3. financial (sources of financing, cost of capital, debt amortization period).

Unlike other simulation codes, INCAS's generation costs model is not a mere input section of the code: An original calculation routine allows derivation of the construction costs of each successive NPP unit on the basis of its output size, design technology, and learning accumulation.

INCAS's premise is that the cost of n NPP units is not equal to n times the cost of one NPP.

INCAS starts from a reference, first-of-a-kind construction cost for a given design technology and a given reactor size and calculates construction costs of each successive NPP unit of the same design technology, through a top-down estimation approach and on the basis of a given construction strategy in terms of schedule and site location. In particular, the code takes into account

1. economies of scale
2. co-siting economies due to sharing of fixed costs by NPPs built and operated on the same site
3. construction cost savings due to modularization effects, which are size dependent
4. learning economies, at both a single site level and worldwide, with two different learning accumulation and decay laws
5. effect of delay in the construction period
6. cost of financing during the construction period.

First of a kind engineering (FOAKE) and manufacturing (FOAKM) costs, as well as reactor concept, research and development, and licensing costs (the part not covered by public funding) should be analyzed through a bottom-up approach, not adopted in the current INCAS strategy since a detailed cost breakdown for new-generation SMRs and LRs is not available. It is assumed that these costs are included in the FOAK NPP costs both for SMRs and LRs, then recovered on successive NPP units through a learning curve. These costs contribute to the economies-of-scale penalization for SMRs. It has to be considered that the smaller scale of SMRs and the consequent number of units to be deployed will allow them to position quite soon on their "maturity" phase.

Co-siting economies, modularization, and learning economies contribute to the economies of multiples. It applies to multiple NPP projects but obviously is more evident for SMR projects that, given a total power output, require more NPP units to be installed.

In addition, SMRs usually benefit from cost savings from design technology simplification: Specific saving factors have to be provided to the model on the basis of expert elicitation.

All of these phenomena have been modeled on the basis of open literature values and implemented in the INCAS code: 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:

$$\delta = \frac{\mathrm{OCC}^C(S_{\mathrm{SMR}}, N_{n,\mathrm{SMR}}, N_{World,\mathrm{SMR}}, M_{\mathrm{SMR}}, D_{\mathrm{SMR}})}{\mathrm{OCC}^C(S_{\mathrm{LR}}, N_{n,\mathrm{LR}}, N_{World,\mathrm{LR}}, M_{\mathrm{LR}}, D_{\mathrm{LR}})} = \vartheta_{ES} \times \vartheta_l \times \vartheta_{CS} \times \vartheta_M \times \vartheta_D \ , \tag{1}$$

where

OCC^C = overnight construction cost [\$/kW(electric)]

S = reactor size [MW(electric)]

N_n = number of units of the same type built on the same site

N_{World} = number of units of the same type built in the world

M = degree of modularity

D = innovative design solution feature characterizing the power plant

ϑ_{ES} = factor related to economies of scale

ϑ_l = factor related to learning

ϑ_{CS} = factor related to co-siting

ϑ_M = factor related to modularity

ϑ_D = factor related to design enhancements.

The overall construction cost scaling factor δ for the SMR against the LR is then obtained by multiplying the ϑ_i parameters.

Lastly, SMRs benefit from shorter construction times as compared to LRs of the same design type, which accounts for further savings in the financial costs.

INCAS offers the user both a high degree of automatism and the option to intervene in the cost modeling structure by changing the curve parameters to override the default settings with specific, proven information.

The investment model, relying on a discounted cash flow model, combines the input data to produce a comprehensive set of indicators that give a holistic investment financial appraisal, such as internal rate of return (IRR) of the investment project, levelized cost of electricity (LCOE), capital at risk, capital structure ratios (e.g., debt to equity, maximum debt outstanding, debt cover ratio, debt duration), investment payback time (PBT), cash flow profile, and net present value (NPV) of the project cash flows, interest cover ratio, and profitability index.

IRR and LCOE are calculated iteratively as the discount rate and electricity sale price, respectively, that drive the NPV of the investment project to breakeven:

$$\mathrm{NPV} = 0 = \sum_t \frac{\mathrm{CF}_t(ee_{price})}{(1+\mathrm{IRR})^t} \tag{2}$$

$$\mathrm{NPV} = 0 = \sum_t \frac{\mathrm{CF}_t(\mathrm{LCOE})}{(1+K_e)^t} \ , \tag{3}$$

where CF_t is the cash flow of year t, which is a function of the electricity price ee_{price}, and K_e is the cost of capital (equity).[a]

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 that allow one to meet a target project profitability; LCOE is then calculated with respect to the scenario input settings.

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 reinvesting the cash inflows from the early deployed NPPs' operations in the later NPP units' construction.

If any positive free cash flow exists for an NPP, after covering debt obligations, it is diverted to cash-deficit NPPs under construction, to 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, reinvesting self-generated equity resources in the project, at an appropriate IRR (see Fig. 2, where i and j are indexes running over all the NPPs of the deployment scenario).

Self-financing may represent a relevant financing source for staggered, modular investments in multiple NPPs, which makes a project financially affordable by investors with limited up-front investment capabilities. Figure 3 summarizes the structure of the financial cash flows for the investors.

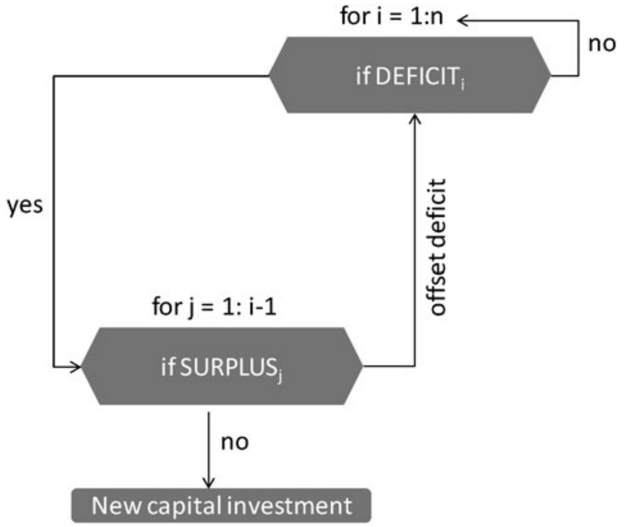


Fig. 2. Self-financing routine in INCAS model.

Despite its multisite-level analysis capability, INCAS will be employed in this work on simple, single-site business cases to test the economic performance of different sizes of NPPs under different scenario conditions.

Four SMRs built on the same site are compared to one stand-alone monolithic LR with the same total power output at site level. These test cases refer, as an example, to a 1320 MW(electric) LR unit compared with four 330 MW(electric) SMRs.

The construction schedule simulated for the SMRs' deployment is staggered to benefit from learning accumulation in the construction activity of successive units, thus progressively decreasing construction costs. Moreover, the SMRs' construction scalability allows the generation of self-financing; this effect on business profitability is analyzed through the comparison of different construction schedules (as shown in Figs. 4 and 5).

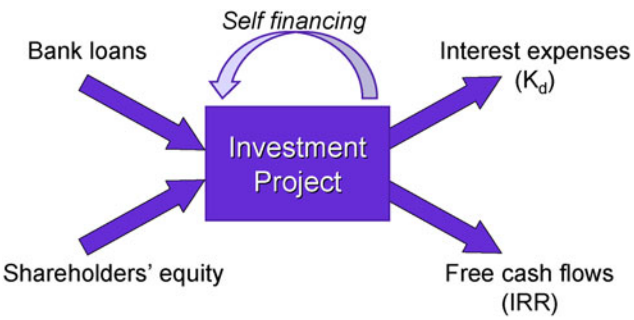
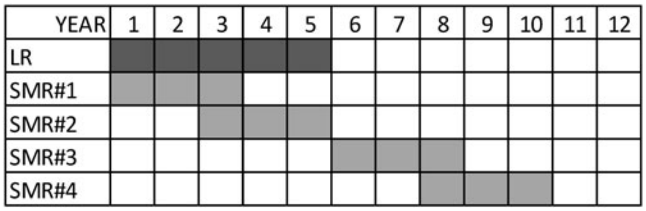


Fig. 3. Typical investment project input and output.

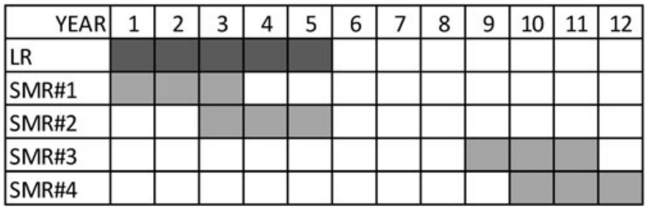
---

[a] Regarding the cost of capital, a key factor is the risk premium the financial markets will set for SMRs. Five key parameters will impact the risk premium: (1) the price volatility of the electricity market; (2) the price volatility of the competitive fuels such as natural gas; (3) the perceived lag time in investments heavily impacted by the licensing/design paradigm for SMRs; (4) the carryover risks that LRs have experienced in the marketplace—could be country-specific; and (5) the overall market risk for all capital projects. SMRs and LRs would account for different risk premiums set by financial markets, due to different risk profiles. Project profitability may be evaluated on the basis of the NPV of an investment, requiring the setting of a proper cost of capital and risk premium, or on the basis of the IRR, which is a dimensionless parameter not affected by the scale of the investment and not requiring the setting of a proper cost of capital as a discount rate. It can be argued that the investment flexibility allowed by SMRs may be valued by investors[14] and translated to lower risk premium. Risk premium would then be differential among LRs and SMRs (see component 5 above), but to avoid the introduction of additional assumptions on the financial market behavior in the risk pricing, the IRR approach has been adopted: The IRR of the LR and SMR projects has been calculated as representing the intrinsic profitability. IRR is defined as the discount rate that balances the NPV calculation and therefore represents the capital remuneration of the specific project.



YEAR	1	2	3	4	5	6	7	8	9	10	11	12
LR	■	■	■	■	■							
SMR#1	▨	▨	▨									
SMR#2			▨	▨	▨							
SMR#3						▨	▨	▨				
SMR#4								▨	▨	▨		

Fig. 4. LR and SMR construction: short SMR deployment schedule (base case).



YEAR	1	2	3	4	5	6	7	8	9	10	11	12
LR	■	■	■	■	■							
SMR#1	▨	▨	▨									
SMR#2			▨	▨	▨							
SMR#3									▨	▨	▨	
SMR#4										▨	▨	▨

Fig. 5. LR and SMR construction: long SMR deployment schedule.

III. TEST CASES

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 summarized as unpredictable cash flows over exceptionally extended project lifetimes, on account of the lack of consolidated information and experience on both construction costs and operating performance and the economics of new-generation reactors. Moreover, cash flow expectations are potentially undermined by possible regulation changes, reactor operation underperformance, or electricity market downturn. If risk allocation countermeasures are undertaken, a nuclear investment project may enhance its bankability and hence its financial attractiveness and feasibility.

The level of risk allocation and the main economic features of the energy market environment may affect a nuclear investment in a significant way. To investigate different scenario conditions for NPP deployment, both a merchant business case, based on the rules of the liberalized electricity and capital markets, and a supported business case, referred to special risk-mitigation policies and conditions, are defined and tested with INCAS. The scenarios' key features are summarized in Table III.

The supported case is derived from the analysis of two case studies: Olkiluoto 3 (Ref. 14) in Finland and the South Texas Project[15–18] in the United States. 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 nonprofit power generation business case, where a shareholders' cooperative consortium will off-take the power output through long-term electricity sales 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, mainly just invested capital recovery, they nevertheless 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 of bank loans allow for low capital costs.

In the supported case, a target 10% shareholders' capital remuneration rate is considered to justify the entrepreneurial business risk, whereas 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 risks, and banks will ask for tighter loan covenants. This in turn might increase the probability of financial default while decreasing shareholders' profitability to an extent that the project financing scheme would not be viable. For this reason, the financing of the not-supported nuclear project is 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[22] assuming an 8% interest rate on debt for merchant case project financing, a conservative 7% interest rate on balance sheet financing is assumed for the INCAS test case, for corporations with less than 50% of nuclear power business in their business portfolios.

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

Once the deployment schedule (Figs. 4 and 5), the financial data (Table III), and the scenario data (Table IV) have been identified, the test cases involving alternative LR and SMR 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.

IV. RESULTS AND DISCUSSION

IV.A. Project Cost-Effectiveness

LCOE has been calculated in both the supported and merchant business cases as the minimum electricity sale

TABLE III

Financing Data from Case Studies and for INCAS Test Cases

	Olkiluoto 3	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[a]	Up to 80% of total construction cost[b]	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[19–21]
Market risk	Long-term electricity sales contracts at fixed price[c]	89% of power output sold through long-term contracts	Long-term electricity sales contracts	Sales at spot price
Cost of equity capital (K_e)	0%	Not disclosed	10%	15%
Engineering, procurement, and construction (EPC) type of contract	Turnkey	No	Target price with incentives	On cost basis
Tax rate	0% (nonprofit)	$18/MWh tax credit on first 8 yr of operation	30%	30%
Financing scheme	20% equity; 5% corporate financing; 75% project financing	Not applicable	100% project financing	100% corporate financing

[a] Detail of the State guarantees: €610 million as export credit from French State (COFACE); €100 million from Swedish State (AB Svensk Exportkredit-SEK).
[b] On bank loans, standby insurance for regulatory delays.
[c] At cost-price basis, estimated to be <25 €/MWh.

TABLE IV

Scenario Reference Data for INCAS Test Cases

Input	LR Base Value	SMRs Base Value	Rationale and Bibliographic References
Plant operating lifetime (yr)	60	60	Same technology enhancement and reliability[19] for LR and SMRs.
Estimated construction period (yr)	5	3	LR total construction time considering the most common LR design installed worldwide.[23–28] Reduced construction time for SMRs due to reduced size and assuming design simplification.[23,29,30]
Overnight construction cost [$/kW(electric)]	4000	4284 (average)	LR value[22] as conservative with respect to recent estimations[31–33] while being optimistic with respect to recent contracts.[34] SMR capital costs estimated from LR capital costs.[9]
O&M costs ($/MWh)	9	10.8	LR cost considering a deep investigation for U.S. reactors[35] (conservative value since O&M costs for new NPP should be lower than previous generation reactors, due to design simplification and passive safety features[36]). SMR O&M costs estimated from LR cost[37] (SMRs to LR ratio = 1.2).
Fuel cycle costs ($/MWh)	6.7	6.7	Conservative estimation[19] as compared with other studies.[20,21,32,38–40]
D&D sinking fund ($/MWh)	3	5.9	A fee of 2 €/MWh is reasonable for LR, according to a thorough survey on decommissioning costs.[41] SMR decommissioning costs estimated from LR cost[42,43] (SMRs to LR ratio = 2).
Inflation (%, annual)	2	2	Average inflation rate for developed countries.[44]
Wholesale ee_{price} USA ($/MWh)	57.2	57.2	Average wholesale electricity price by North American Electric Reliability Corporation region, 2001–2007 (Ref. 45).
Plant availability (%)	93	95	Assumptions based on estimations for Gen III/Gen III+, LR (Ref. 46), and SMR (Ref. 1).

price that covers all the project life cycle costs. In particular, LCOE 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 shown in Table V, SMR deployment has to set higher LCOE (+7% in the supported case) to grant the same capital remuneration between the LR and SMRs, because of its higher construction costs. The calculation procedure sets the required capital remuneration (IRR) and considers the ee_{price} as an output: LCOE is the minimum sale ee_{price} needed to cover capital remuneration.

INCAS shows that SMR deployment is less cost-effective than LR deployment (higher LCOE) in the supported case: Lower power installed rate implies later revenues whose time value is penalized by actualization. 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 LCOE 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 better able to cope with higher capital costs.

Figure 6 shows the trend of LCOE as a measure of the economic performance of SMR deployment, which improves on that of the LR with the cost of debt increasing.

TABLE V

Cost-Effectiveness and Shareholders' Profitability for LR and SMRs in Supported and Merchant Cases, at Short Deployment Schedule

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

SMRs are revealed as a more suitable option for the merchant case's capital remuneration requirements: When financial leverage and/or cost of debt are higher, SMRs are able to limit interest capitalization and debt accumulation due to shorter PBT for each NPP module. Their financial behavior is more stable and less sensitive to high cost of capital (see Sec. IV.B).

Table VI itemizes the results related to the OCC calculation for the SMRs, according to Eqs. (1), (2), and (3) of the INCAS model and adopted in the INCAS simulation of the different deployment scenarios.

The loss of economies of scale represents 69% construction cost increase on the first SMR module in terms of \$/kW(electric), as compared to the LR. Nevertheless, the four SMR units together gain cost effectiveness through the economies of multiples: The difference in LCOE 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 four SMRs (average cost saving factor is 91.7% on the four units with respect to the first one). Co-siting economies (i.e., sharing of fixed costs) 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 the LR's: As compared to LR, they decrease from +25% of first unit to +7% on average over all SMRs [\$4284/kW(electric) with respect to \$4000/kW(electric) for LR].

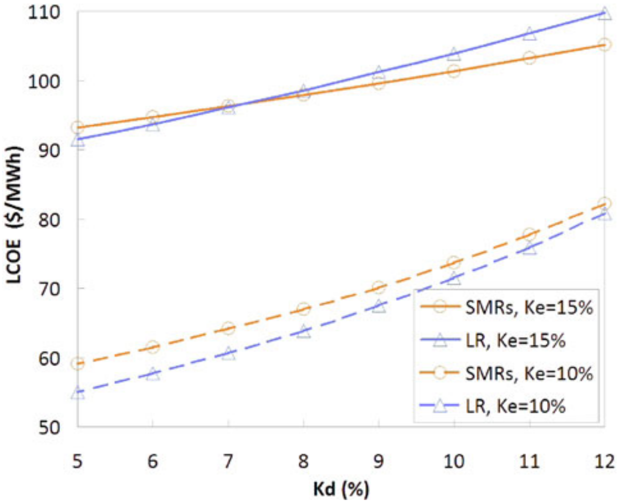


Fig. 6. LCOE trend at increasing cost of debt K_d, at different cost of equity K_e (merchant case, solid lines; supported case, dashed lines).

Total capital investment includes not only the OCC but also interest during construction (IDC).

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

As an example, in the supported case the SMRs' IDC is 50% lower than LRs, with a net saving of \$297 million; as a consequence, SMRs' total capital investment cost (TCIC) is only \$83 million higher than LRs. The TCICs for LRs and SMRs are nearly the same (\$5961 million and \$6045 million, respectively).

That is argued by the shorter construction time for each SMR and the consequent shorter investment PBT, accounting for limited interest capitalization during the

TABLE VI

OCC Factors

	SMR #1	SMR #2	SMR #3	SMR #4	SMR Average	LR
Economies of scale ϑ_{ES} (%)	169	169.3	169.3	169.3	169.3	100
Learning ϑ_l (%)	100	92.5	88.4	85.6	91.7	100
Co-siting economies ϑ_{CS} (%)	100	93.0	90.6	89.4	93.2	100
Modularization ϑ_M (%)	86.8	86.8	86.8	86.8	86.8	100
Design savings ϑ_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 [\$/kW(electric)] per reactor unit	5000	4300	4006	3829	4284	4000

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, whereas SMRs' IDC will increase only from 5% to 7%.

IV.B. SMRs' Construction Schedule Strategy

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, which can be reinvested 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 the self-financing source because the PBT is shorter for the early units.

This option is not available to the single monolithic LR. It allows the limiting of the up-front capital outlay (equity plus debt) to below that needed by the LR, as shown in Fig. 7.

Self-financing generation may be fostered by diluting the SMRs construction schedule over a longer period of time. With ee_{price} above \$70/MWh, debt plus equity investment needed to build four SMRs is lower than for LR, due to self-financing contribution (arrow A in Fig. 7). With ee_{price} at \$80/MWh, self-financing represents 11% of SMRs' TCIC; in the base case, i.e., 10-yr construction schedule (short deployment schedule), self-financing accounts for \$641 million on TCIC \$6063 million (arrow B in Fig. 7). If deployment of SMRs is rescheduled over 12 years in a way that the first two modules work as a "cash provider" to finance the construction of the last two units, then self-financing (\$1115 million) increases to 19% of TCIC (arrow C in Fig. 7).

With a long deployment schedule and \$900/MWh ee_{price}, self-financing accounts for \$1571 million, namely 26% of SMRs' TCIC.

It has been already shown that given the same capital remuneration (K_e = IRR), SMRs are slightly less cost-effective (higher LCOE) than LR. If the ee_{price} is higher than LCOE, as in the case of a free-floating price according to the electricity market and in growing economies, hence assuming growing electricity demand, lower cost-effectiveness translates into lower IRR for SMRs as compared to LR, given the same ee_{price}. This is shown in Fig. 8, where the profitability curve of SMRs is lower than that of LR at a different ee_{price}. Figure 8 also shows that the 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 for the LR, but it slightly reduces project profitability, due to revenue shifts onward.

Moreover, recourse to self-financing reduces the up-front capital disbursement and the IDC arising from bank loans, notwithstanding that it represents an equity capital source, with higher cost than bank loans.

A trade-off stands out between profitability maximization and construction schedule dilution in order to increase self-financing, assuming that the latter is simply synthesized 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 on the shareholders'

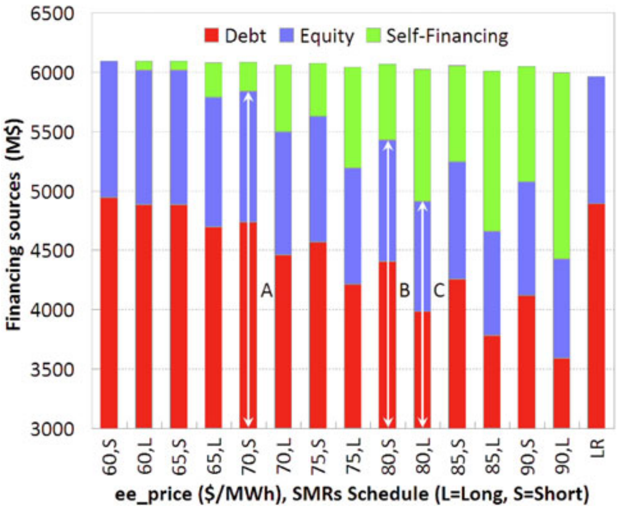


Fig. 7. Financing sources (debt, equity, self-financing) at different ee_{price} and SMRs deployment schedules for the supported case.

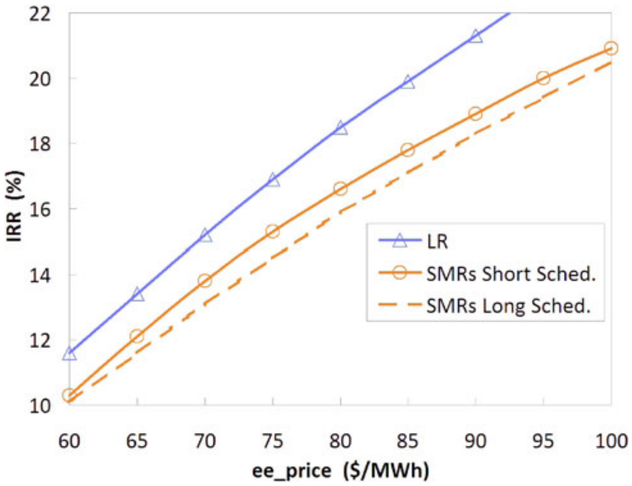


Fig. 8. Project profitability (IRR) with different ee_{price} and construction schedule for the supported case.

business and investment structure (e.g., for-profit corporation, nonprofit consortium of utilities and industries as in the Olkiluoto 3 case, or government involvement). Nevertheless, investment scalability offers an additional strategic option and flexibility.

IV.C. Sensitivity Analysis: Project Risk

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. 9, which shows the input parameters with the highest influence on the project economic performance for the merchant case. The same behavior of the project profitability applies in the supported case sensitivity analysis.

The IRR variation is assessed as a percentage of its base value ($K_e = 15\%$), according to a $\pm 10\%$ change in the input parameters (with the exception of the NPP availability, whose increase is bounded to $+5\%$ due to the assumption of a reference value already near to the maximum of 100%). The ee_{price} is left free to float according to electricity market price dynamics and is assumed as an input to calculate the capital remuneration (IRR).

For almost all the parameters and business cases, the sensitivity of the LR's profitability is wider than that of the SMRs; this indicates a lower financial risk for SMRs as a general trend. In particular, SMRs tend to cope better 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 10% of its base value, i.e., roughly 1% in absolute value.

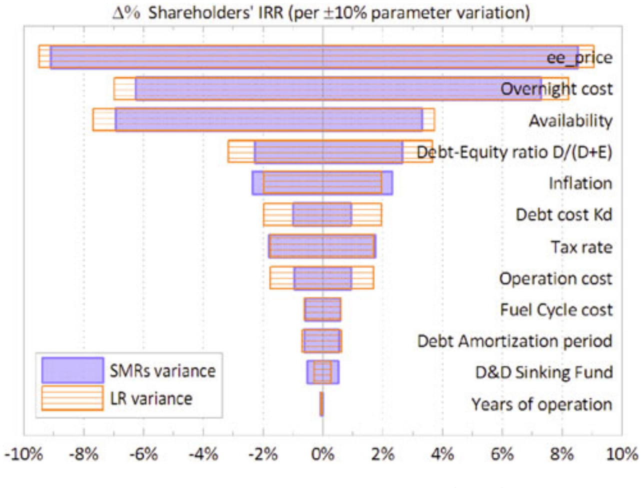


Fig. 9. Sensitivity of project profitability (IRR) to main parameter input data variation for the merchant case.

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.

Because of the staggered construction of SMRs over a longer period, SMRs are more sensitive to inflation, which 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 sales contracts, if allowed by market rules in liberalized electricity markets, it is possible to offset 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.

Given the capital intensive nature of nuclear investment, a delay in the NPP construction period may be particularly burdensome for the project economic performance; construction delay is another relevant source of business risk. Nevertheless, when delay applies to a monolithic LR, all capital investment cost is affected and increases proportionally to the time delay. Considering a four SMR investment project, a construction delay affecting the first NPP unit or, at worst, the first two units could be reasonably assumed. The underlying hypothesis is that technical and management failures and inefficiencies on first units construction can be recovered, e.g., through learning or suppliers' reselection, in such a way that later SMR units benefit from construction and assembly process tuning to meet the construction schedule.

Figure 10 shows that multiple SMRs may better cope with construction delay than a single LR, when delay is longer than 1 yr and applies to the first SMR only, since SMR projects become more cost-effective than LR (lower LCOE). The same occurs when delay affects SMR units 1 and 2. Nevertheless, when construction delay is longer than 2.7 yr, SMRs 1 and 2 struggle to provide self-financing for the construction of later units 3 and 4, and debt and IDC increase until the whole project economics may underperform those of LR.

V. CONCLUSIONS

This work aimed to test the economies-of-multiples feature as a new model paradigm in nuclear reactor deployment, compared to traditional economies of scale, through the INCAS economic simulation tool.

The benefits of this paradigm are evident in the case study, where four SMRs are considered against a single,

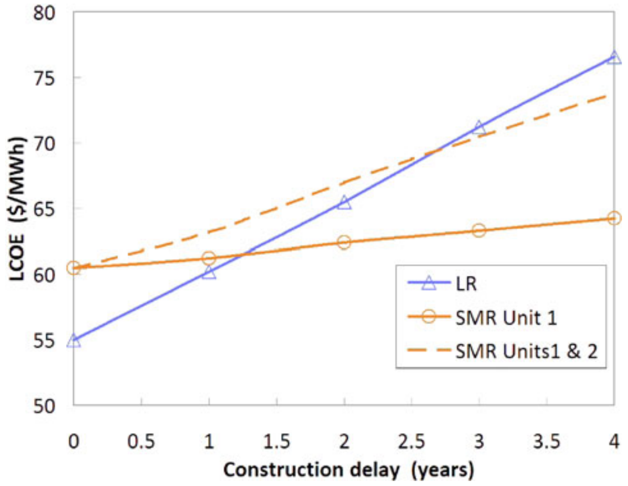


Fig. 10. LCOE trend for LR and SMRs with construction delay (years).

monolithic LR, on account of their intrinsic investment scalability.

INCAS shows that a "modular" investment project in multiple SMR power blocks may be able to offset 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 cost escalation and financial risk (i.e., profitability variance). The possibility to stagger the units' deployment in time makes SMRs an affordable option for investors with limited financing capabilities and a chance to contain the average capital exposure. The LR, as their counterpart, grants a better economic performance in supported scenarios, where market conditions are less volatile and where OCCs 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, whereas 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 an understanding of the key input parameters that may affect the economic performance of the nuclear investment. They confirmed the incidence of capital costs on the profitability outcome. Capital costs include OCCs and financing costs. About construction costs, the paper deals with a "top-down" approach, where OCCs depend largely on modeling assumptions based on learning curve, modularization curve, design saving factor, and multiple units curve. Related uncertainties deserve to be the object of a further investigation, although their estimation will not be straightforward due to the substantial lack of suitable data referred to current SMR projects. A sensitivity analysis on the above-mentioned parameters should be appropriate. Other factors may affect construction and financing costs, such as the licensing process, including emergency planning requirements. Detailed analysis of FOAK and fixed costs has not been performed in this work, although these items deserve further investigation in future developments of INCAS economic modeling through a "bottom-up" approach in order to individuate the differential (dis)advantages brought in by SMRs.

Further developments of the INCAS code will aim to investigate the economic benefits of investment flexibility allowed by multiple NPPs, to be performed through the real options theory. Advanced applications of INCAS will concern multiple site investment projects, involving multiple LR and SMR deployments. Moreover, a Monte Carlo approach will be implemented, to capture the impact of the stochastic distribution and variance of input data on the model output. Other nonfinancial parameters, the so-called "external factors" such as design robustness, spinning reserve management, and risks during construction, will be considered as well.

NOMENCLATURE

CF = cash flow ($ millions/yr)

ee_{price} = electricity selling price ($/MWh)

IDC = interest during construction ($ millions)

IRR = internal rate of return (%)

K_e = cost of equity (%/yr)

K_d = cost of debt (%/yr)

LCOE = levelized cost of electricity ($/MWh)

NPV = net present value ($ millions)

OCC = overnight construction cost [$/kW(electric)]

PBT = payback time (yr)

TCIC = total capital investment cost ($ millions)

REFERENCES

1. M. D. CARELLI et al., "The Design and Safety Features of the IRIS Reactor," *Nucl. Eng. Des.*, **230**, 151 (2004).

2. "B&W mPower," U.S. Nuclear Regulatory Commission: http://www.nrc.gov/reactors/advanced/mpower.html (current as of August 31, 2010).

3. R. JOHNSON, J. POTTORF, M. LEONARD, M. MODARRES, M. CORRADINI, V. K. DHIR, and J. REMPE, "Severe Accident Prevention and Mitigation Features of the

NuScale PWR Design," *Proc. ANS Winter Meeting*, Washington, D.C., November 15–19, 2009, American Nuclear Society (2009).

4. G. PETERSON, R. H. KIMPLAND, and D. M. COATES, "Compact, Self-Regulating Nuclear Reactor," *Trans. Am. Nucl. Soc.*, **98**, 729 (2008).

5. N. UEDA, I. KINOSHITA, A. MINATO, S. KASAI, T. YOKOYAMA, and S. MARUYAMA, "Sodium Cooled Small Fast Long-Life Reactor 4S," *Prog. Nucl. Energy*, **47**, *1–4*, 222 (2005).

6. S.-H. KIM, K. K. KIM, J. W. YEO, M. H. CHUNG, and S. Q. ZEE, "Design Verification Program of SMART," *Proc. GENES4/ANP2003*, Kyoto, Japan, September 15–19, 2003.

7. "Status of Innovative Small and Medium Reactor Designs 2006. Reactors with Conventional Refueling Schemes," IAEA-TECDOC-1485, International Atomic Energy Agency, Vienna, Austria (2006).

8. D. T. INGERSOLL, "Deliberately Small Reactors and Second Nuclear Era," *Prog. Nucl. Energy*, **51**, 4 (2009).

9. M. D. CARELLI, P. GARRONE, G. LOCATELLI, M. MANCINI, C. MYCOFF, P. TRUCCO, and M. E. RICOTTI, "Economic Features of Integral, Modular, Small-to-Medium Size Reactors," *Prog. Nucl. Energy*, **52**, 403 (2010).

10. "Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems. INPRO Manual—Environment," Vol. 7, IAEA-TECDOC-1575, Rev. 1, International Atomic Energy Agency, Vienna, Austria (2008).

11. L. VAN DEN DURPEL, A. YACOUT, D. WADE, and H. KHALIL, "DANESS—Dynamic Analysis of Nuclear Energy System Strategies," Int. Conf. Global 2003, New Orleans, Louisiana, November 16–20, 2003.

12. "FINPLAN: Model for Financial Analysis of Electric Sector Expansion Plans," International Atomic Energy Agency: http://www.iaea.org/OurWork/ST/NE/Pess/PESSenergymodels.html (current as of August 31, 2010).

13. S. BOARIN and M. E. RICOTTI, "INCAS—INtegrated Model for the Competitiveness Analysis of Small-Medium Sized Reactors: User's Manual and Test Cases," Version 1.1, CSA Report, International Atomic Energy Agency (Mar. 2010).

14. A. DI GIULIO, G. LOCATELLI, and M. MANCINI, "Ritardi e aumenti di costi nella realizzazione del reattore nucleare Olkiluoto 3 in Finlandia," *Impiantistica Italiana*, **XXIII** (2010).

15. U.S. CONGRESS, "Title XVII: Incentives for Innovative Technologies," U.S. Energy Policy Act, 42 U.S.C. 16511–16514 (2005).

16. *Code of Federal Regulations*, Title 10, "Energy," Part 609, RIN 1901–AB27, "Loan Guarantees for Projects That Employ Innovative Technologies," U.S. Department of Energy (2009).

17. CPS ENERGY, "Assumptions for 2009 Resource Plan Analysis" (June 29, 2009).

18. "Cities Aggregation Power Project Announces Long-Term Electricity Contract with Luminant, Could Save Texas Cities Millions," RedOrbit (Sep. 18, 2009).

19. Y. DU and J. E. PARSONS, "Update on the Cost of Nuclear Power," MIT-CEEPR, Massachusetts Institute of Technology (2009).

20. M. AYRES, M. MACRAE, and M. STOGRAN, "Levelised Unit Electricity Cost Comparison of Alternate Technologies for Baseload Generation in Ontario," Canadian Energy Research Institute (2004).

21. "The Economic Future of Nuclear Power," University of Chicago (2004).

22. D. FINON and F. ROQUES, "Contractual and Financing Arrangements for New Nuclear Investment in Liberalised Markets: Which Efficient Combination?" CeSSA Working Paper, European Regulation Forum on Supply Activities (2008).

23. "Heavy Manufacturing of Power Plants," World Nuclear Association (2009).

24. "DOE NP2010 Nuclear Power Plant Construction Infrastructure Assessment," MPR-2776, U.S. Department of Energy (2005).

25. "Economic, Employment and Environmental Benefits of Renewed U.S. Investment in Nuclear Energy: National and State Analysis," Oxford Economics (2008).

26. C. R. KENLEY et al., "U.S. Job Creation Due to Nuclear Power Resurgence in the United States," Vols. 1 and 2, INEEL/EXT-04-02384, Idaho National Engineering and Environmental Laboratory (2004).

27. "The UK Capabilities to Deliver a New Nuclear Build Programme," Nuclear Industry Association (2008).

28. "Study of Construction Technologies and Schedules, O&M Staffing and Cost, Decommissioning Costs and Funding Requirements for Advanced Reactor Designs," Dominion Energy, Bechtel Power Corporation, and TLG (2004).

29. "A Technology Roadmap for Generation IV Nuclear Energy Systems," U.S. Department of Energy Nuclear Energy Research Advisory Committee and Generation IV International Forum (2002).

30. "A Roadmap to Deploy New Nuclear Power Plants in the United States by 2010," U.S. Department of Energy (2001).

31. K. VAILLANCOURT, M. LABRIET, R. LOULOU, and J.-P. WAAUB, "The Role of Nuclear Energy in Long-Term Climate Scenarios: An Analysis with the World-TIMES Model," *Energy Policy*, **36**, *7*, 2296 (2008).

32. "Nuclear Power Generation Cost-Benefit Analysis," U.K. Department of Trade and Industry (2007).

33. "Assumptions to the Annual Energy Outlook 2009," DOE/EIA, U.S. Department of Energy (2009).

34. "The Economics of Nuclear Power," World Nuclear Association (2010).

35. J. KOOMEY and N. E. HULTMANC, "A Reactor-Level Analysis of Busbar Costs for US Nuclear Plants, 1970–2005," *Energy Policy*, **35**, *11*, 5630 (2007).

36. R. A. MATZIE and A. WORRALLY, "The AP1000 Reactor—The Nuclear Renaissance Option," *Nuclear Energy*, **43**, *1*, 33 (2004).

37. M. CARELLI, C. W. MYCOFF, P. GARRONE, G. LOCATELLI, M. MANCINI, M. E. RICOTTI, A. TRIANNI, and P. TRUCCO, "Competitiveness of Small-Medium, New Generation Reactors: A Comparative Study on Capital and O&M Costs," *Proc. 16th Int. Conf. Nuclear Engineering (ICONE 16)*, Paper 48931, Orlando, Florida, May 11–15, 2008.

38. "World Energy Outlook 2009," International Energy Agency (2009).

39. H. STAUFFER, "Beware Capital Charge Rates," *Electricity Journal*, **19**, *3*, 81 (2006).

40. "The Role of Nuclear Power in Europe," World Energy Council (2007).

41. "Decommissioning Nuclear Power Plants: Policies, Strategies and Costs," OECD Nuclear Energy Agency (2003).

42. G. LOCATELLI and M. MANCINI, "Competitiveness of Small-Medium, New Generation Reactors: A Comparative Study on Decommissioning," *J. Eng. Gas Turbines Power*, **132**, *10*, 102906 (2010).

43. G. LOCATELLI and M. MANCINI, "End of Life of Nuclear Power Plants: The Decommissioning Cost of New Small Medium Reactors vs. Large Reactors," *Proc. 9th Int. Conf. Modern Information Technology in the Innovation Processes of the Industrial Enterprises (MITIP 09)*, Bergamo, Italy, October 15–16, 2009.

44. "The World Factbook: Inflation Rate," U.S. Central Intelligence Agency (2010).

45. "Average Electricity Wholesale Price," U.S. Department of Energy, Energy Information Administration (2010).

46. T. L. SCHULZ, "Westinghouse AP1000 Advanced Passive Plant," *Nucl. Eng. Des.*, **236**, 1547 (2006).