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Handbook of Small Modular Nuclear Reactors

Edited by

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Economics and financing of small modular reactors (SMRs)

10

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10.1 Introduction

A description of the economic and industrial potential features of small modular reactors (SMRs) was given in 2010 by the US Secretary of Energy (Chu, 2010):

> '[…] Small modular reactors would be less than one-third the size of current plants. They have compact designs and could be made in factories and transported to sites by truck or rail. SMRs would be ready to 'plug and play' upon arrival. If commercially successful, SMRs would significantly expand the options for nuclear power and its applications. Their small size makes them suitable to small electric grids so they are a good option for locations that cannot accommodate large-scale plants. The modular construction process would make them more affordable by reducing capital costs and construction times. Their size would also increase flexibility for utilities since they could add units as demand changes, or use them for on-site replacement of aging fossil fuel plants. […] These SMRs are based on proven Light Water Reactor technologies and could be deployed in about 10 years'.

The goal of this chapter is to present the most relevant economic and competitive aspects related to the SMR concept.

10.1.1 Basic definitions and concepts

The nuclear sector commonly clusters nuclear power plant (NPP) life-cycle costs as capital cost, operation and maintenance, fuel and decommissioning.

- *Total capital investment cost (or capital cost)*: an all-inclusive plant capital cost, or lump-sum up-front cost. This cost is the base construction cost plus contingency, escalation, interest during construction (IDC), owner's cost (including utility's start-up cost), commissioning (non-utility start-up cost), and initial fuel core costs for a reactor (EMWG, 2007).
- *Operation and maintenance (O&M)*: costs inclusive of, but not limited to: (i) actions focused on scheduling, procedures, and work/systems control and optimization; (ii) performance of routine, preventive, predictive, scheduled and unscheduled actions aimed at preventing equipment failure or decline with the goal of increasing efficiency, reliability, and safety (Sullivan *et al*., 2010).
- *Fuel cost*: the sum of the costs for the fissile/fertile materials (natural uranium, low-

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enrichment uranium, highly enriched uranium, mixed oxide fuel, uranium-thorium, etc.) and the enrichment process of the fuel in fissile materials, plus other materials used in the fuel assemblies (zirconium, graphite, etc.), services required to produce the needed materials (mining, milling, conversion, enrichment, fabrication), fuel fabrication, shipment and handling, costs of spent-fuel disposal or reprocessing and waste (including low-level, high-level and transuranic waste) disposal.

- *Decommissioning*: costs for the administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility. The actions will ensure the long-term protection of the public and the environment, and typically include reducing the levels of residual radionuclides in the materials and on the site of the facility, to allow the materials' safe recycling, reuse, or disposal as 'exempt waste' or as 'radioactive waste' and to allow the release of the site for unrestricted use or other use (IAEA, 2007a).

These costs contribute in different ways to the economics of a NPP. In general it is possible to compare them using one of the most important indicator for policy makers. This indicator, usually called levelized unit electricity cost (LUEC) or levelized cost of electricity (LCOE), represents a unit generation cost of electricity, accounting for all the NPP life-cycle costs and is expressed in terms of energy currency, typically [$/KWh]. For both large reactors (LRs) and SMRs the capital cost is the main component (50–75%) of the LCOE, followed by O&M and fuel, as shown in Table 10.1. From this consideration arises the opportunity to analyse in detail the nature of the capital cost item. In accordance with the glossary provided by EMWG (2007), Table 2 lists and clusters all the main accounts included in the capital cost.

If the construction time increases, almost all the cost items, apart from the equipment, are affected by such increase. In particular, the cost items affected by a time schedule increase are as follows:

- Labour cost: on the construction site of a reactor plant, thousands of people are employed.
- Rent fees for building infrastructures (e.g. special cranes).
- Escalation: the amount of all the cost items tends to increase because of a generalized inflation mechanism; the inflation rate may specifically relate to the price dynamics of the main inputs, such as structural materials, energy, etc.

Table 10.1 LCOE cost components

	OTA (1993)	**DOE (2005)**	**MacKerron *et al.* (2005)**	**Williams & Miller (2006)**	**Gallanti & Parozzi (2006)**	**Locatelli & Mancini (2010b)**
Capital costs	62%	71.9%	60–75%	48.7%	68%	59%
O&M costs	12%	11.19%	5–10%	23.25%	13%	24%
Fuel costs	26%	16.91%	8–15%	27.22%	15%	13
Decommissioning costs	0%	0%	1–5%	0.84%	4%	5%

Sources: Carelli *et al.* (2008a); Locatelli and Mancini (2010b).

Table 10.2 Example of Code of Accounts for capital costs

Account number	Account title	Account number	Account title
1	*Capitalized Pre-Construction Costs*	36	PM/CM Services Offsite
11	Land and Land Rights	37	Design Services Onsite
12	Site Permits	38	PM/CM Services Onsite
13	Plant Licensing	39	Contingency on Indirect Services
14	Plant Permits	**Base Construction Cost**	
15	Plant Studies	*4*	*Capitalized Owner's Costs*
16	Plant Reports	41	Staff Recruitment and Training
17	Other Pre-Construction Costs	42	Staff Housing
19	Contingency on Pre-Construction Costs	43	Staff Salary-Related Costs
2	*Capitalized Direct Costs*	44	Other Owner's Capitalized Costs
21	Structures and Improvements	49	Contingency on Owner's Costs
22	Reactor Equipment	*5*	*Capitalized Supplementary Costs*
23	Turbine Generator Equipment	51	Shipping and Transportation Costs
24	Electrical Equipment	52	Spare Parts
25	Heat Rejection System	53	Taxes
26	Miscellaneous Equipment	54	Insurance
27	Special Materials	55	Initial Fuel Core Load
28	Simulator	58	Decommissioning Costs
29	Contingency on Direct Costs	59	Contingency on Supplementary Costs
Direct Cost		**Overnight Construction Cost**	
3	*Capitalized Indirect Services Costs*	*6*	*Capitalized Financial Costs*
31	Field Indirect Costs	61	Escalation
32	Construction Supervision	62	Fees
33	Commissioning and Start-Up Costs	63	Interest During Construction
34	Demonstration Test Run	69	Contingency on Financial Costs
Total Field Cost		**Total Capital Investment Cost**	
35	Design Services Offsite		

Source: EMWG (2007).

- Interest during construction: financial costs related to the capital remuneration increase with the investment duration.

In addition to the cost increase, each day of construction schedule delay represents a loss in terms of missed electricity generation and potential revenues.

Once construction and commissioning are completed, the NPP enters the operation mode. In this phase almost all the costs are fixed (Parsons and Du, 2009). A large part of the operation and fuel costs is independent of the electricity generated (fixed costs). Even if the plant has a low capacity factor, the labour cost, which is the main component of O&M costs, does not change, and neither does most of the maintenance cost.

As a consequence of the essentially fixed nuclear generation costs, the NPP manager's interest is generally to run the plant at its target (i.e. nominal) capacity. For this reason nuclear power is most suited for base load production.

10.1.2 Construction cost estimation

To evaluate the construction costs that, as said, represent the main component of nuclear LCOE, two approaches are usually adopted: top-down cost estimation and bottom-up cost estimation.

- *Top-down estimation*. The cost is calculated starting from a reference, known cost value, then considering the most important cost drivers that characterize the economics of that specific technology to derive scaled or proportional costs. Regarding the power plant industry, these drivers are: the plant size, the number of units to build, the site location, etc. This procedure is particularly appropriate when the plant design is still in the early phase of development, or when the plant design is characterized by a high level of complexity and number of systems as to make the cost estimation of each of them a hard task with a decrease in the reliability of the end result. An application of top-down cost estimation to SMRs is presented in Carelli *et al*. (2010).
- *Bottom-up cost estimation*. The cost analysis is carried out at 'component level' and the final cost is the sum of all of the costs related to the components manufacturing, assembling, operation, etc.

Once estimated through the above-mentioned procedures, the life-cycle costs, together with the cost of financing (equity and debt) and tax burdens, may be elaborated to perform a discounted cash flow (DCF) analysis. The DCF analysis provides the most relevant indicators of economic performance, such as the internal rate of return (IRR), the net present Value (NPV), the (LUEC) and the payback time (PBT) (see Figure 10.1). Several studies indicate that optimism in the cost estimation of large projects, such as civil and transport infrastructures, power plants, etc., is a common characteristic. This phenomenon may be observed in the case of NPPs, which are historically characterised by delay in construction and cost escalation (Locatelli and Mancini, 2012a). In order to provide a reliable cost estimation of SMRs, it is important to understand why the estimations of NPP costs, as well as large engineering projects, are usually so inaccurate and how to improve this process. Under this perspective,

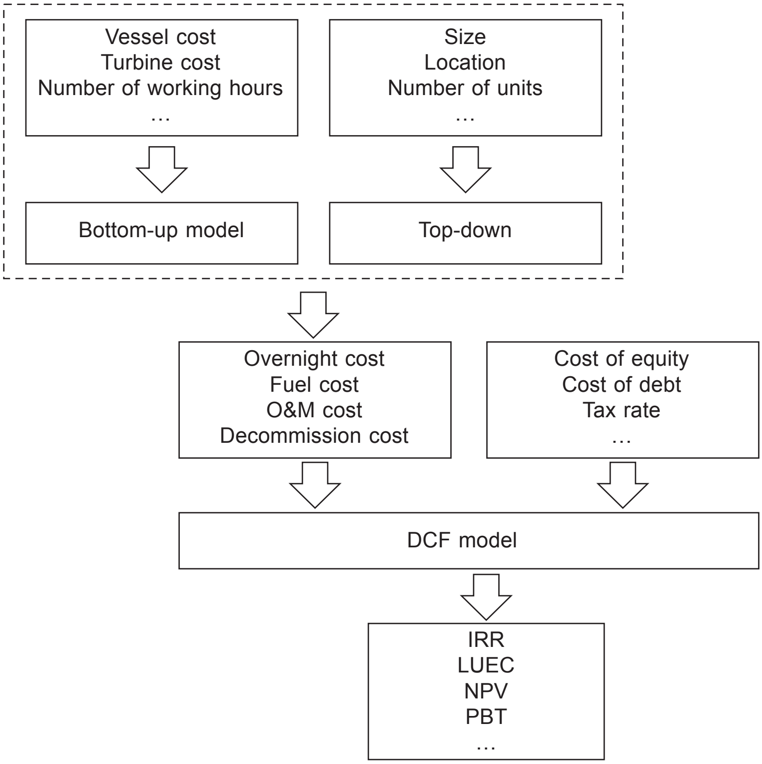

Figure 10.1 Economic evaluation of power plants.

Flyvbjerg *et al*. (2003) show that the availability and reliability of data about large projects affect the estimation. The authors identify two macro-categories of causes to explain inaccuracy in the cost forecast: (i) inadequacy of the methodologies and (ii) strategic data manipulation. The latter, combined with 'optimism bias', is responsible for most of the cost escalation.

10.2 Investment and risk factors

The investment decision in an industrial activity largely depends on the capability of the project to adequately recover and remunerate the initial capital expenditure. The uncertainty of the capital cost estimation, i.e. the initial investment, as mentioned in Section 10.1.1, affects the ability to make a reliable estimation of the investment profitability. The uncertainty affects the scenario conditions, the project realization and operation; as a result, the stream of income generated by the project is also affected by uncertainty. Therefore, expected profitability has a degree of risk embedded and a series of different possible outcomes, depending on the realization of stochastic variables. Investment in liberalized electricity markets, as in most of the European and

North American countries, compels investors to include uncertainty in their business plan analysis and to give risk as much relevance as profitability into their decision making. The key variables to the financial performance of the investment project are 'forecast' in order to get a reasonable estimation of the project profitability and economic soundness. All this considered, NPPs represent a long-term investment with deferred payouts. Moreover, the nuclear industry is very capital-intensive. This means that a high up-front capital investment is needed to set up the project and a long payback period is needed to recover the capital expenditure.

The longer this period, the higher is the probability that the scenario conditions may evolve in a different, unfavourable way, as compared to the forecasts. As an example, market price of electricity might be driven downwards by unexpected market dynamics; unexpected operating or design drawbacks might also undermine plant availability. A capital-intensive investment requires the full exploitation of its operating capability and an income stream as stable as possible. On a long-term horizon, a low volatility in a variable trend might translate into a widespread range of realizations of the variable value. This condition is common to every capital-intensive industry. Nevertheless, some risk factors are specific or particularly sensitive to the nuclear industry: typically, the public acceptance, the political support in the long-term energy strategy, the activity of safety and regulatory agencies.

For these reasons nuclear investment is usually perceived as the riskier investment option among the power generation technologies (Figure 10.2). Clearly, risk is not the only or the most relevant criterion in the selection of a power generation technology. Besides risk and cost, other strategic and economic issues are included in a technology investment evaluation, such as the power generation independence, the power density (as compared to the land occupation), the power supply stability (baseload), the electricity price stability, etc. The key risk factors affecting a nuclear investment project are tentatively listed and classified in Table 10.3.

Capital cost and construction lead-time have pre-eminent importance. Construction time and cost overruns are considered to be the most adverse occurrence able to undermine the nuclear power economics. Throughout the construction period, the project will be exposed to commodity price risk, vendor credit risk, engineering and construction contract performance risk, supply chain risk, sovereign risk, regulatory risk, etc. The construction phase is the most affected by the investment risk. The magnitude of a project overrun is often difficult to estimate while construction proceeds and even more difficult to rein in (Dolley, 2008). The ability to estimate construction cost in the past has proved very limited, as confirmed by US data reported in Table 10.4.

Thus, financing of nuclear power is affected by risk perception. Risk has a cost, which is transferred to the cost of capital in terms of 'risk premium', as a remuneration for possible negative outcomes (Damodaran, 2011). The 'rating' associated with an investment project represents the probability of financial default: as far as the 'rating' is low (i.e. the risk is high), the risk premium applied on the cost of capital (equity or debt) is high. Therefore nuclear projects usually bear high cost of money, compared with other energy sources. For this reason and for the long debt duration, IDCs represent a relevant part of the capital cost (Figure 10.3): any increase in the

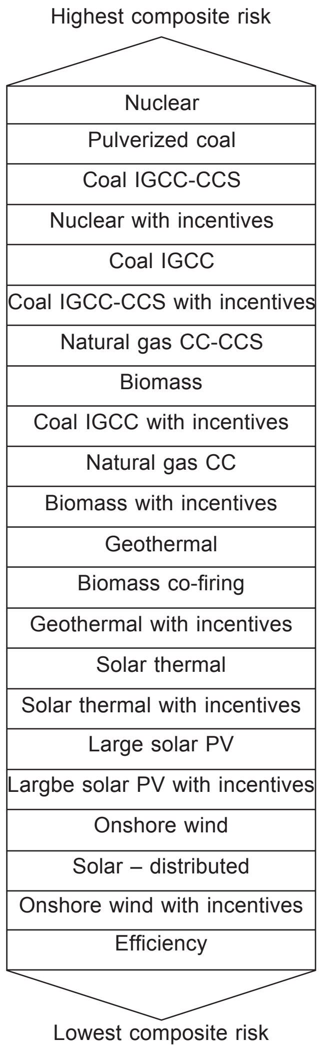

Figure 10.2 Risk ranking of generation resources for new power plants (Binz *et al*., 2012). Key: IGCC: integrated gasification combined cycle; CC: carbon capture; CCS: carbon capture and separation.

cost of capital would be a significant burden on the project economics. Besides risk premium considerations, IDCs are also heavily affected by the construction period, where financial exposure is the highest and the project pays compound interests on the invested capital.

Hence nuclear business risk derives from:

- capital intensive nature, with huge sunk costs and high financial exposure during very long PBTs;

Table 10.3 **Main risk factors of capital-intensive and nuclear-specific industry**

Risk factors, common to capital-intensive industries	Risk factors, nuclear-specific
• Complex and highly capital intensive: high up-front capital costs • Cost uncertainty • Completion risks: construction supply chain risks • Long lead times (engineering & construction, etc.) and long payback periods • Sensitive to interest rates • Plant reliability/availability/load factor • Market price of output (i.e. electricity)	• Unstable public support • Negative public acceptance • Regulatory/policy risks (revised safety measures) • Decommissioning and waste cost/liabilities

Table 10.4 **Projected and actual construction costs for US nuclear power plants**

Construction starts		Average overnight costs		
Year initiated	Number of plants	Utilities' projections (thousands of dollars per MW)	Actual (thousands of dollars per MW)	Overrun (percent)
1966–1967	11	612	1279	109
1968–1969	26	741	2180	194
1970–1971	12	829	2889	248
1972–1973	7	1220	3882	218
1974–1975	14	1963	4817	281
1976–1977	5	1630	4377	169
Overall average	13	938	2959	207

Source: Kessides, (2012).

- very long-term market forecast reliability;
- unexpected external unfavourable events (such as natural events, public acceptance/political support withdrawal) or intrinsic drawbacks to the project economics (such as construction time and cost overruns, operating unavailability).

SMRs may represent a valuable option to mitigate several among the risk factors previously discussed. Due to their features, SMRs are able to reduce the severity of many risk factors in pre-construction, supply chain, construction and operating phases (Locatelli *et al.*, 2011a). An IAEA investigation (Barkatullah, 2011) on the topic reached the conclusion that SMRs may present mitigation factors against some

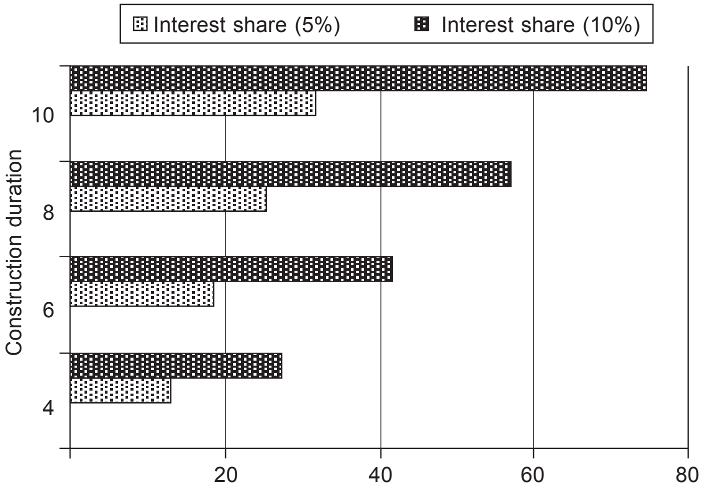

Figure 10.3 IDC as % on overnight capital costs, with different construction duration (years) and cost of money (5%, 10%) (Barkatullah, 2011).

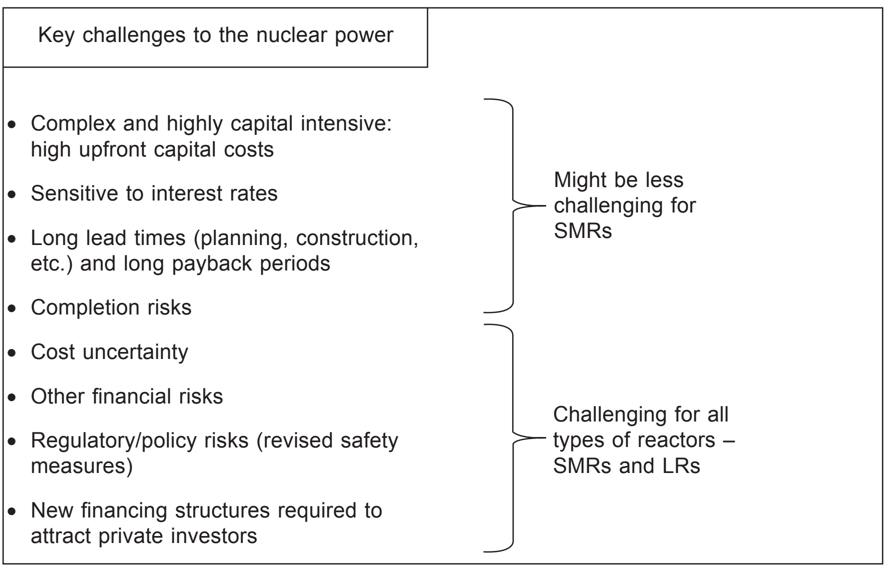

Figure 10.4 Risk factors: differential impact on SMRs and large reactors. Adapted from Barkatullah (2011).

major financing challenges of nuclear power (Figure 10.4). In particular, lower up-front investment of an SMR and low construction lead-time are key features able to decrease the financial risk of the investment. These are discussed in the following sections.

10.2.1 Reduced up-front investment and business risk diversification

SMRs may represent a viable option to decrease the average capital at risk in the nuclear business, with respect to LR projects. Financial risk is related to the amount of invested capital. Banks usually apply credit risk control through loans portfolio diversification. The same applies to the shareholder investor (e.g. a utility). Very high capital exposure in a single project represents a stress on the balance sheet and a relevant financial and industrial risk exposure, so that a nuclear generation project could be viewed as a 'bet the farm' endeavour for a shareholder utility, due to the size of the investment and the length of time needed to commission a nuclear power facility.

A model has been proposed for relating the risk premium to the risk size (Goldberg and Rosner, 2011). The assumption is that the risk premium associated with a project is a function of the wealth of the sponsoring entity, as might be measured by, for example, NPV and debt to equity ratio. The mathematical expression for this relationship shows risk premium rising at an exponential rate as the size of the project approaches the size of the investor-firm.

If the investment size in different base load technologies is compared with the average annual revenues of a utility (Figure 10.5), it becomes evident that SMRs should be viewed more favourably by the investor community and bear lower risk premium than very large reactors. (Examples of current annual revenues for some US utilities: Exelon – $23.5 billion, Duke Energy – $19.6 billion.)

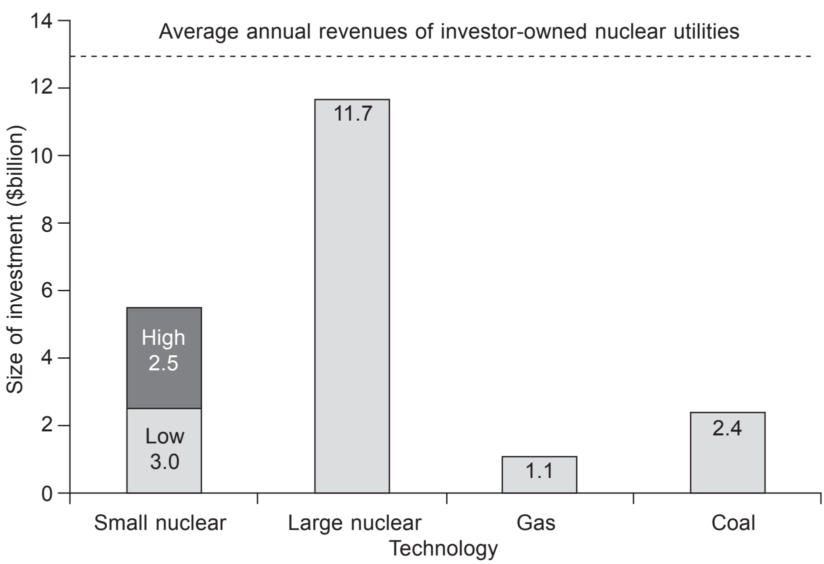

Figure 10.5 Comparison of size of investment (i.e., overnight cost) with average annual revenues of investor-owned nuclear utilities. 'Large nuclear' investment represents twin-unit GW-scale plant (Goldberg and Rosner, 2011).

A rating methodology reported in Table 10.5 shows that business diversification in low versus high risk (i.e. nuclear) businesses is among the risk metrics considered in the evaluation of the merit of credit of a company. In this sense, SMRs allow a better industrial risk diversification, on account of a limited investment on total capital budget. In case of small-sized market or reduced capital budget availability, by including SMR in a portfolio mix it is possible to grant a business diversification,

Table 10.5 Moody's rating methodology for electric utilities

Broad rating factors	Broad factor weighting	Rating sub-factor	Sub-factor weighting
Rating factor weighting – regulated electric utilities			
Regulatory framework	25%		25%
Ability to recover costs and earn returns	25%		25%
Diversification	10%	Market Position Generation and Fuel Diversity	5% 5%
Financial strength, liquidity and key financial metrics	40%	Liquidity CFO pre-WC/Debt CFO pre-WC + Interest/Interest CFO pre-WC – Dividends/Debt Debt/Capitalization or Debt/Regulated Asset Value	10% 7.50% 7.50% 7.50% 7.50%
Rating factor weighting – unregulated electric utilities			
Market assessment, scale and competitive position	25%	Size and scale Competitie position and market structure	15% 10%
Cash flow predictability of busines model	25%	Fuel strategy and mix Degree of integration and hedging strategy Capital requirements and operational performance Contribution from low-risk/high-risk business	5% 5% 5% 10%
Financial policy	10%		
Financial strength metrics	40%	Cash flow/debt Cash flow interest coverage Retained cash/debt Free cash flow/debt	12.5% 10% 12.5% 5%

Source: Goldberg and Rosner (2011).

that would be pre-empted by a large plant, reducing the investment risk (Locatelli and Mancini, 2011a).

10.2.2 Control of construction lead times and costs

One of the main concerns for investors is unexpected delays during construction of a NPP and the related cost escalation. Faced by the above-mentioned risks, several investors stand 'frozen' and wait and see the market evolution, the strategies of their competitors or wait for a more mature phase of a specific reactor plant concept to exploit cost reduction and learning accumulation.

As argued by IAEA (Barkatullah, 2011), reduced plant size and complexity and design simplifications, enabled by the SMRs, should allow:

- better control on shorter construction lead-time – leaner project management (e.g. higher factory-fabrication content, modularization of reactors);
- lower supply chain risks – increased number of suppliers and reduced need of special and *ad hoc* manufacturing and installations;
- better control on construction costs – if plant complexity of gigawatt electric (GWe)-scale nuclear plants has been a driver of cost escalation (Grubler, 2010), SMRs should enable economies from standardization and accelerated learning. The ability to meet cost projection should also improve.

10.2.3 Control over market risk

Multiple SMRs represent both a 'modular' design concept and a 'modular' investment model: multiple SMRs may offer the investor a step-by-step entry in the nuclear market. As long as multiple SMRs are deployed with a staggered schedule, the investor has the option to expand, defer or even abandon a nuclear project, to adjust the investment strategy in order to catch early market opportunity or to edge a market unexpected downturn. The investment involves sequential steps with multiple 'go' or 'not-to-go' decisions that allow management to respond to changes in the market or in the regulation environment, or to adapt to technological breakthroughs. The risk edging capability of a modular investment such as multiple, staggered SMRs is enhanced compared with a monolithic LR. This flexibility against future uncertainty can be measured by the real option analysis and exploited to face the investment risks (Locatelli *et al.*, 2012).

10.3 Capital costs and economy of scale

Economic competitiveness of a power generation technology depends on the ability to provide electricity with affordable LCOE, and/or of repaying the investors by means of adequate cash inflows, granting a minimum acceptable capital remuneration compared to the level of risk and to the PBT duration. Given the relevance of the capital costs in the nuclear electricity generation cost (i.e. given the 'capital intensity' of the nuclear investment), capital cost, including overnight construction and financial costs, has a relevant impact on the key economic performance indicators.

With very few SMR projects under construction and no actual data on overnight actual costs, cost estimation of SMRs is usually performed on a top-down basis, as recommended in Section 10.1.2, starting from available information on large, advanced pressurized water reactor (PWR) units, as a starting reference cost. (The only SMR reactors under construction in 2014 were CAREM in Argentina, HTR-PM in China and the twin barge-mounted KLT-40S in Russia (Akademik Lomonosov), planned to be located near Vilyuchinsk. Construction was started in 2007 and, owing to some economic-financial problems, the plant is now expected to be completed in 2016 (http://www.world-nuclear.org/info/inf33.html)). Carelli *et al.* (2010) present a parametric methodology to compute the overnight construction cost of SMRs, based on the application of dimensionless coefficients, related to the most important differential economic features between SMRs and LRs: e.g. expected learning effect, degree of modularization, co-siting economies and simplified design. Many of these factors are dependent on the number of units built on the same site and on the plant output size.

The above-mentioned design-related economies, learning effects on costs, plant modularization, and co-siting economies account for an expected reduction of multiple plant construction cost. Based on these factors, it is estimated that the SMR economic paradigm might bring unit construction cost in line with expected costs of Generation III+ (GENIII+) large PWRs, thus overcoming the loss of economy of scale. Figure 10.6 provides a qualitative sketch of SMR economic features' recovering the loss of economy of scale on unit construction cost, as far as multiple SMRs are considered an alternative investment opportunity to LR power stations, with the same overall power at site-level.

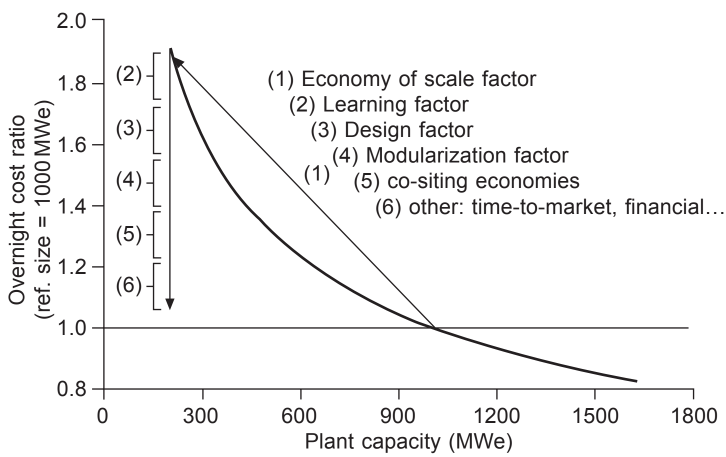

Figure 10.6 Top-down estimation of overnight construction costs of SMR: qualitative trend (Barenghi *et al.*, 2012).

Actual information on LRs under construction (in western countries) gives evidence of relevant time-schedule and cost overruns. It must be highlighted that this comparison applies on SMR versus large NPP *expected* costs. This means that capital cost overruns, which seem to systematically affect *actual* costs of large NPP projects, are not considered. When *actual* costs of construction are considered, it is expected that, as stated in Section 10.2.2, SMRs might have better control on construction schedule and costs, and higher probability to meet capital budgeting. The main assumption is that, the simpler the design, the easier the procurement, manufacturing and assembling process and the project management.

In any case, a possible cost overrun on a single SMR unit would necessarily have a lower incidence on total investment than in an LR, due to the lower cost of a single SMR.

If a time/cost schedule mismatch affected the initial SMR unit(s), the simple fact of fractioning a nuclear power station into multiple smaller units makes unlikely that such a mismatch could be repeated on all of the units, on account of learning and improved practices in the supply process, construction work and project management.

Thus, as far as *actual* construction costs are considered, including possible cost overruns and financial interests escalation, SMRs might improve their cost competitiveness against LRs, as compared to the mere theoretical expectations.

Economy of scale has been the key driver of the nuclear industry over the past. The evolution of nuclear power technology is characterized by a constant trend in the output size increase. The US utilities converged to 1000–1400 MWe sized plants, French NPPs were scaled from 950 to 1550 MWe in the 1971–1999 period, up to the recent 1600 MWe European Pressurized Reactor (EPR). As a capital-intensive industry, nuclear power generation technology pursued the economy of scale law, to decrease the incidence of fixed costs over a higher output base.

In principle, SMRs are heavily penalized by the loss of economy of scale: applying a typical scale exponential law (usually with coefficient in the range 0.6–0.7), a stand-alone 335 MWe SMR may bear 70% cost increase on a unit base (€/kWe) over a 1340 MWe LR (Carelli *et al.*, 2007a). SMR units with smaller size would bear a greater penalty (up to 350%); this should be recovered by other means, in order to uphold cost competitiveness.

Nevertheless, the evidence of construction cost escalation of GW-scale reactors triggers considerations about the applicability of the economy of scale law on NPPs (Grubler, 2010): an increase in the plant scale apparently produces an increase in the intrinsic complexity, which challenges the project management and other activities in the plant design, construction and assembly. This translates in construction schedule delays and dramatic cost overruns. (For example Olkiluoto, Flamanville, South Texas Project, Vogtle and, more recently, Hinkley Point 3, Olkiluoto and Flamanville are under construction, while US-based projects are in the early site preparation phase; therefore the cost overrun have different nature in the two cases.) Projected cost and the lead time of the new projects under construction in Europe or under construction in US, have all been dramatically revised upwards, with a rate of increase per year of delay in the plant commissioning in excess of 20% (Table 10.6). This cost

Table 10.6 **Cost increase and commissioning delays of NPP currently under construction**

	Initial cost estimate	Revised cost estimate	Delay on commissioning
Olkiluoto 3 (Finland)	3 Bn€	8.5 Bn€	From 2009 to 2018
Flamanville (France)	3.3 Bn€	8.5 Bn€	From 2012 to 2016
Levy County (US)	5 Bn€	24 Bn€	From 2016 to 2024
South Texas Project (US)	5.4 Bn€	18.2 Bn€	Expected by 2006, then project abandoned in 2011
Hinkley Point (UK)	10 Bn£	16 Bn£	Commissioning delayed from 2017 to 2033

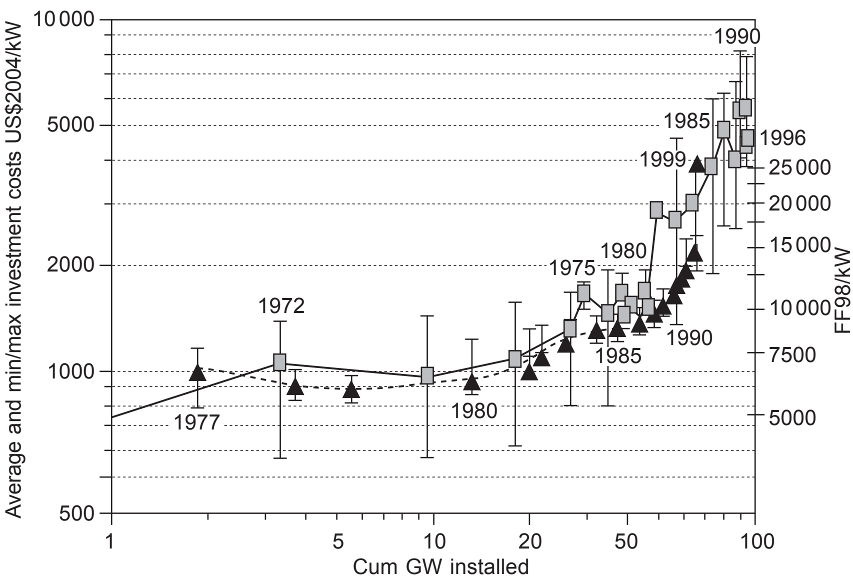

Figure 10.7 Average and min/max reactor construction costs per year of completion date for US and France versus cumulative capacity completed (Grubler, 2010).

escalation coherent with a historical trend of construction cost increase over time (Figure 10.7).

A detailed analysis of the French NPP fleet (all PWRs) shows that construction costs and schedule have increased over time with the size of the plants (Figures 10.8 and 10.9). The French PWR program exhibited substantial real cost escalation, in spite of a unique institutional setting allowing centralized decision making, regulatory stability and dedicated efforts for standardized reactor designs. This evidence challenges the applicability of a learning economy on NPP construction, as far as 'traditional' NPP are considered, without introducing the concepts of design simplification and modularization, discussed in the following Sections 10.5.1 and 10.5.2.

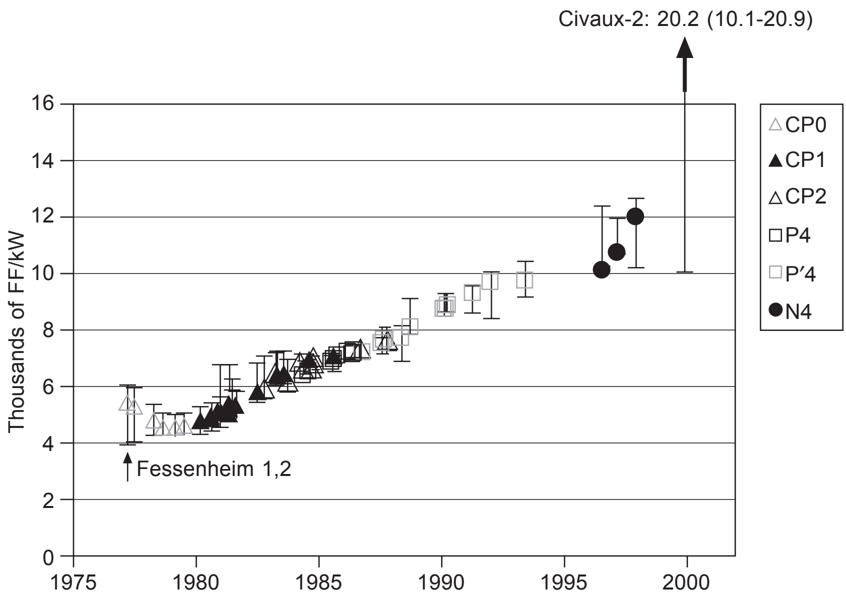

Figure 10.8 Inferred specific reactor construction costs (1000FF98/kW) per French PWR reactor sorted by reactor type and completion date (year of criticality), best guess and min/max uncertainty ranges of estimates (Grubler, 2010).

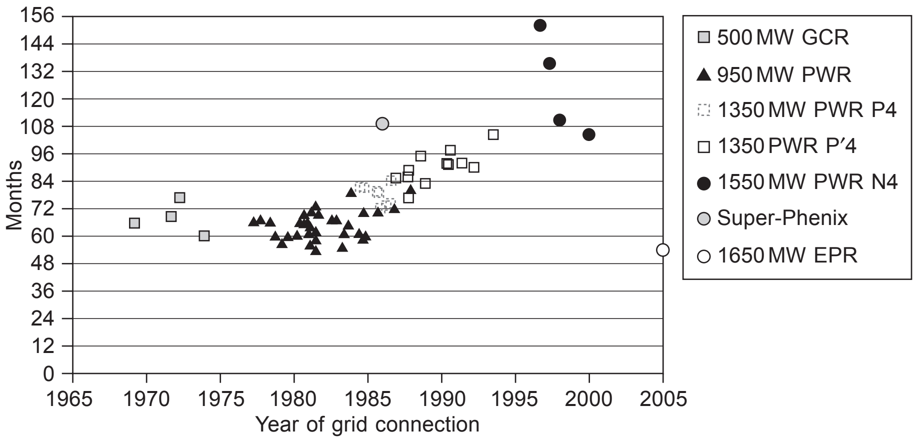

Figure 10.9 Construction time of French reactors (construction start to first grid-connection, in months). Data on 1650 MWe EPR reactor in Flamanville is a projection submitted by the French authorities to the IAEA. Source: IAEA PRIS Data Base (2009) http://www.iaea.org/pris/home.espx. GCR = graphite gas reactors (Grubler, 2010).

10.4 Capital costs and multiple units

When a fleet of multiple NPP units are considered, some competitive factors intervene, to reduce the incidence of capital cost on the electricity generated. These factors are enabled and provide their best effect by the deployment of successive NPP of the same type on the same site. These factors are introduced in this chapter, despite not being specific to the SMR plant category, because they are expected to play a relevant role in the SMR economic competitiveness paradigm.

10.4.1 Learning

The contribution of learning (Boarin *et al.*, 2012) applies at various levels: a better work organization on the same site, where the personnel have already had experience in the construction and assembling of previous NPP modules; a learning component in factory fabrication of the equipment; a learning component in the utilization of materials and equipment by more skilled workers, etc. A scale-up of the plant output and the attempt to introduce an original French design, i.e. the N4 reactors, towards the end of the program may only partially explain such an occurrence.

Lovins (1986) presented an interesting theoretical framework, referred to as the Bupp–Derian–Komanoff–Taylor hypothesis, that suggests that with increasing application ('doing'), the complexity of the technology inevitably increases, leading to inherent cost escalation trends that limit or reverse 'learning' (cost reduction) possibilities. In other words, the technology scale-up can lead to an inevitable increase in systems complexity that translates into real-cost escalation, or 'negative learning'. Nevertheless, learning effects have been recorded in technology-advanced industries (Frischtak, 1994); learning effect description was first published by an aeronautical engineer (Wright, 1936).

The learning effect is also visible in the Korean NPP fleet deployment costs: learning accumulation has played an undeniable effect on a progressive cost decrease (Figure 10.10). KHNP, the owner of all 21 of South Korea's operating nuclear power reactors, has held a licensee relationship with Westinghouse since the late 1980s when the US-based company supplied the 945 MWe System 80 nuclear steam supply for Yonggwang 3 and 4. After that, KHNP was able to develop variants of System 80 for its own requirements under technology transfer terms in the license agreement. After introducing domestic innovations and updating technology over time, KHNP came up with the Korean Standard Nuclear Plant (KNSP), then the OPR-1000. The current APR-1400 technology represents a further evolution of that design. The construction and power generation costs of the APR-1400 are reported to be 10% lower than those of OPR-1000 units.

Korean NPP is the evidence that learning economy may apply to construction costs: in this case, learning effect was achieved through a concentrated construction (Figure 10.11), with the deployment of twin/multiple units on the same site and by avoiding substantial design modification in order to attain PWR plant standardization and control design complexity. (Wolsong NPP are PHWR-CANDU, provided by AECL, as the only exception to the PWR design.)

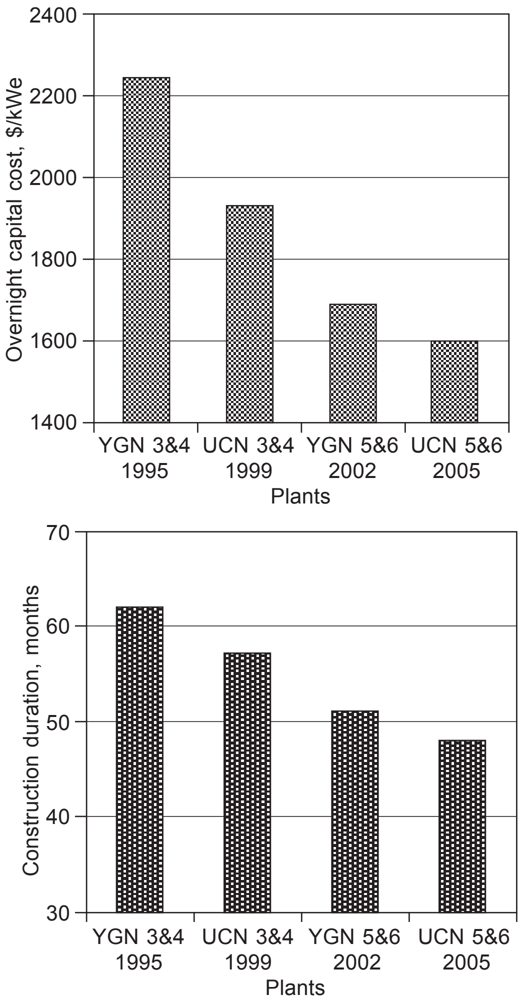

Figure 10.10 Overnight capital costs (in 2005 US dollars; exchange rate 1025 Won/US$) and construction duration (from first concrete to initial critically) of Korean NPP. YGN = Yonggwang; UCN = Ulchin (Matzie, 2005).

It may be argued that in principle, learning accumulation is expected to determine a construction cost and time-progressive decrease of successive NPP units, as it was in the Korean NPP fleet. Nevertheless, as far as western countries are considered, in the real world there is often no evidence of cost and time benefits in large NPP deployment programs. That is why simpler and smaller NPPs, with design modularity and high content of factory fabrication, have a higher chance of controlling complexity and exploiting standardization, enabling learning accumulation on both construction and assembling phases. SMRs are expected to benefit from anticipated learning effects, mostly arising from the construction and assembling of multiple units on the same

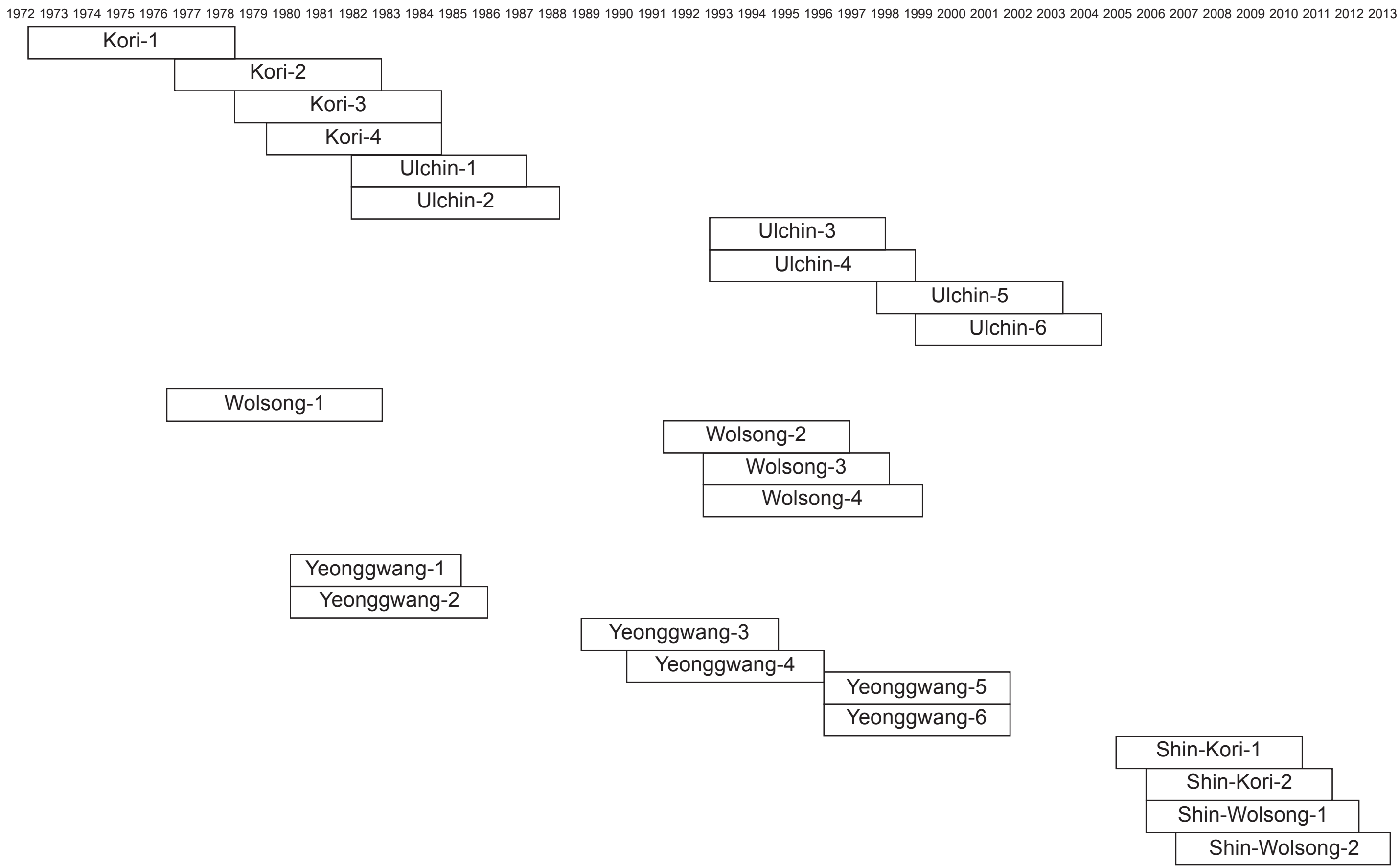

Figure 10.11 NPP deployment program in South Korea (data from http://globalenergyobservatory.org, accessed Feb. 2013).

site. Given the power size of a nuclear site, more SMR units should be fabricated and installed than LRs, with improved chances to learn. General learning accumulation may be recorded at the engineering procurement and construction (EPC) level residing in the human resources knowledge and approach to the project management, and to the organization and procurement issues, such as supplier selection. This learning applies independently of the site location of the new NPP and is therefore indicated as 'worldwide' learning in Figure 10.12. In addition, site-level learning accumulation is also applicable on successive NPP units built on the same site, residing in the best, refined practices and actions by local staff. The magnitude of the two effects is comparable (Boarin and Ricotti, 2011a). The learning effect is destined to fade out over the first five to seven units (Carelli *et al.*, 2010). For this reason, in a mature phase of the market, worldwide learning is not a differential factor for SMRs and LRs, while SMRs keep the benefit from the on-site learning accumulation, which applies in case of multiple units built on the same site.

10.4.2 Co-siting economies

Co-siting economies arise from the cost-sharing of some common structures, systems and services by multiple units built on the same site, decreasing the incidence of some fixed costs and, thus, the penalty of the loss of economy of scale (Boarin *et al.*, 2012).

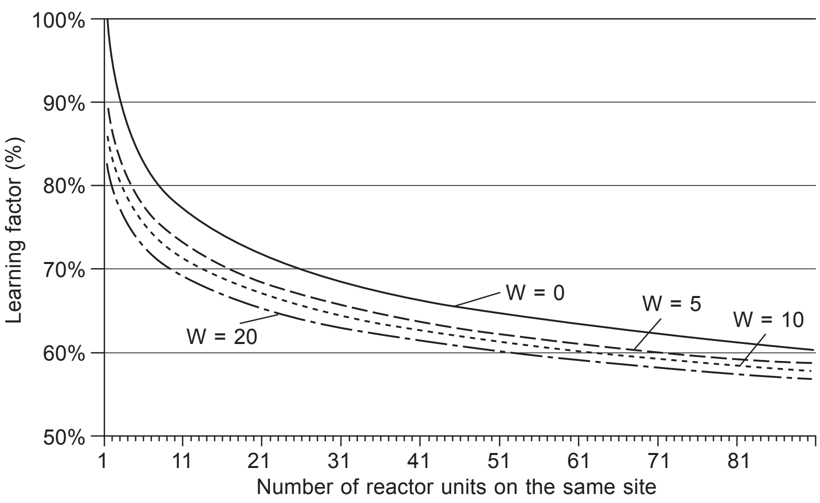

Figure 10.12 Magnitude of overall learning effect (on site + worldwide). W indicates the number of NPP of the same type already built in the world, in other site locations; along the same curve, the magnitude of the 'on-site' learning accumulation may be appreciated, while curves with different value of W indicate the magnitude of the 'worldwide' learning effect. D&D = decontamination and decommissioning (Boarin and Ricotti, 2011a).

10.5 Capital costs and size-specific factors

10.5.1 Modularization

The realization of NPP encompasses the phases of site preparation, construction and start-up. Traditionally, the construction phase of a NPP was performed on site, with specialized workers erecting all the civil structures, nuclear island and balance of plant (BoP) systems starting from raw material and main equipment. Every NPP construction was nearly hand-crafted, specific to the site and the plant design. Conversely, the SMR plant layout may be conceived from its design phase in a number of sub-systems or 'modules' that may be fabricated in a parallel way and then shipped and assembled on-site. The construction of the SMR plant systems on-site is reduced and the fabrication activity tends to be shifted in factory, with the following main benefits:

- controlled work conditions and improved quality standards;
- possibility to apply mini-serial production, fostering the learning accumulation and decreasing the overhead cost of the production lines;
- use of less specialized personnel on-site;
- in principle, reduction of the construction schedule due to the shift from series to parallel activities;
- as a consequence of the previous, lower financial cost escalation during construction.

On account of the smaller size of their components and systems, SMRs can achieve higher degrees of design modularization (Carelli *et al.*, 2007b, 2010). The indivisibility of some subsystems and their large scale in the LR plants compels their construction on-site, while the lower physical size of SMRs allows a greater number of systems to be factory-fabricated and then shipped to the site. Modularization requires more project management effort and transportation complexity. Communication and cooperation between suppliers and contractor has to be accurate, in order to create the schedule and ensure synchrony of the shipments. Modularization turns into real cost and time advantages as long as these additional burdens are counterbalanced by a plant layout simplification and a plant design conceived *ad hoc* to implement and ease the modularization.

10.5.2 Design factor

While modularization deals with a design and fabrication methodology, design factor is related to the specific and peculiar features and enhancements of a given design concept, in order to meet operating requirements with optimized safety, simplicity and economics. Large plants have been optimized for their particular power output. In designing a plant with smaller output, it does not necessarily make sense to just scale down a large system. Usually SMRs are not a mere re-sizing of larger units; they do not represent a way back, but, on the contrary, a further progress in the technology evolution path.

At a smaller size, different design concepts might be possible, which could lead to a more significant capital cost reduction than simple application of the scaling laws from large design would predict (Hayns and Shepherd, 1991). SMR economic rationale also lies on the enhanced passive safety features and design simplifications, often enabled by a small plant scale. The 300–400 MWe safe integral reactor (SIR) in the 1990s and the international reactor innovative and secure (IRIS) in early 2000s paved the way to the understanding of an innovative technological and economic paradigm.

Most Gen III+ reactor designs include some features that may be regarded as passive (i.e. relying on physical laws and not on human intervention for the activation), but small-scale plants can take maximum advantage of such features, due to their physically smaller size or lower power densities, and consequential lower power output. As a result, the elimination of some engineered safety systems might be possible and/or the safety downgrading of some other components. Revised, simplified and more cost-effective plant layout becomes possible, with favourable impact on costs (Carelli *et al.*, 2008a, 2008b).

Along with such design-related cost benefits, the SMR exploit the economics of small 'mass production'. SMRs are conceived to take the maximum advantage from standardization and economy of replication (Kutznetsov and Lokhov, 2011), also referred to as the 'economy of multiples' paradigm. Moreover, SMRs may encompass a broad range of reactor unit sizes. In principle, the lower the size, the higher the loss of economy of scale to be compensated, and the loss of cost effectiveness in terms of generation cost (Figure 10.13).

SMRs rely on the 'economy of multiples' but also on the 'economy of small' in the sense that design-related cost savings are necessary to recover economic

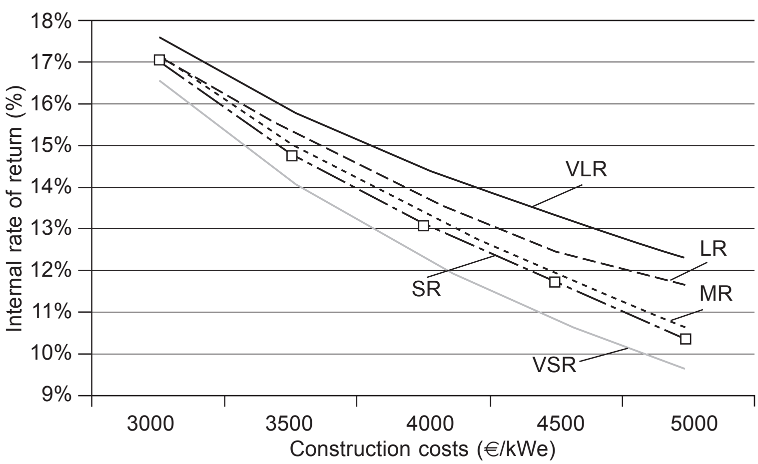

Figure 10.13 Investment profitability of different sized NPP fleets deployed in large sites: VLR = very large reactor (1500 MWe), LR = large reactor (1000 MWe), MR = medium size reactor (350 MWe), SR = small reactor (150 MWe), VSR = very small reactor (50 MWe) (Boarin and Ricotti, 2011b).

competitiveness. The smaller the reactor unit size, the higher must be the design cost savings in order to have the same generation costs as LRs. Some general considerations on cost reduction by design may be drawn from several innovative SMR features, such as the integration of primary loop into the reactor vessel, with the elimination of large loss-of-coolant accident (LOCA), the wide use of passive safety systems with natural circulation of coolant in case of accident, and the elimination of some active components and safety systems. Nevertheless, the design-saving factor that is expected to decrease construction costs of SMRs is strictly dependent on the specific reactor concept. A more reliable estimate could come from a bottom-up cost analysis, referred to the specific plant layout and technical features. In the absence of this information, the economic analysis may consider the design-saving factor as a 'target' value to be achieved in order to equalize the SMR and LR projects' profitability. Thus the economic analysis might offer the manufacturer a sort of indication on a technical and economical goal for the SMR design (Boarin and Ricotti, 2011b). As a consequence, 'very small' reactors (VSR) must come up with additional saving factors (Figure 10.14). Rather, VSRs do not really compete in the same SMR playground since they have other unique requirements, e.g. emphasis on total capital cost, rather than on cost per KW installed, and may have unique applications, such as very small or scattered user areas.

10.6 Competitiveness of multiple small modular reactors (SMRs) versus large reactors

10.6.1 Deterministic scenarios

The economic analysis and comparison between SMRs and LRs, has given great emphasis to the capital costs that dominate nuclear generation costs, as a very capital-intensive technology. The cost comparison between LRs and multiple SMRs has been

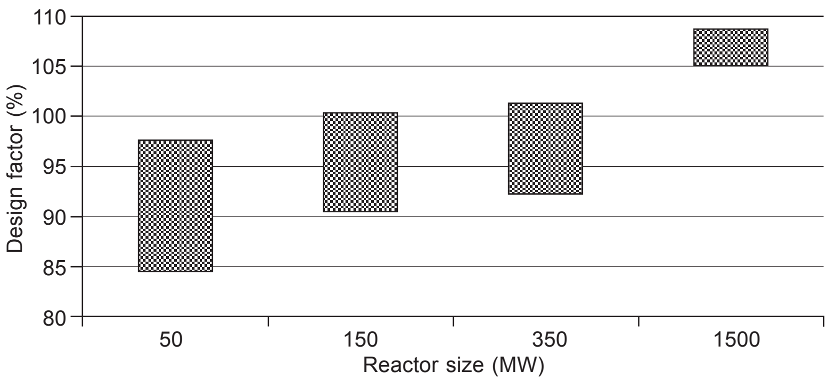

Figure 10.14 Design saving factor ranges of different SMR fleets deployed in large sites (4500 MWe), compared to a very large reactor unit (Boarin and Ricotti, 2011b).

assessed based on very conservative assumptions that almost disregard savings by design at SMRs. Under this assumption and considering ideal or expected construction costs and schedule for LRs (i.e. no delays and no cost overruns), scenario analysis of alternative LR and multiple SMR projects confirms a comparable or higher economic performance of LRs, essentially due to the economy of scale on construction costs. On average, investment IRR and profitability index (PI) of LRs are 1–1.5% higher than SMRs (Boarin and Ricotti, 2009). This slight difference, applied on a relevant project investment value, translates into a significant project value increase. This holds in deterministic scenario conditions, with conservative assumptions on SMRs and ideal assumption for LRs, with no uncertainties affecting the scenario evolution (Boarin and Ricotti, 2011a).

Nonetheless, multiple SMRs have economic features that make them competitive with large NPPs under different perspectives than mere profitability. Multiple SMRs offer financial benefits that encompass intrinsic investment modularity. Investment modularity and scalability are intrinsic features of multiple SMRs that allow adaptation of the investment program to the electricity and financial market evolution. Current projected schedules of SMRs are in the range of four years for the first-of-a-kind (FOAK) and down to two years for a *n*-th-of-a-kind (NOAK), in some designs. This shorter construction time is due mainly to smaller size, simpler design, increased modularization, higher degree of factory fabrication and series fabrication of components.

The shorter construction schedule and the smaller output size make SMRs more readily adaptable to market conditions, both temporally and spatially. The shorter lead times and the plant capacity allow to split the investment in a closer proximity to the market evolution: if not needed, the construction of an additional SMR unit can be avoided whereas a monolithic LR investment may result in an unexpected overcapacity installed. Whereas market conditions are highly uncertain, the SMR modularity translates in adaptability; the investment flexibility in the plant deployment has an associated economic value, which is caught by real option analysis. It is demonstrated that this economic value is positive and accounts for the possibility of avoiding financial losses in market downturn and reaping early revenues in favourable market conditions. The chance to better cope with the probability of a change in the economic environment reduces the gap of competitiveness between LRs and SMRs (Locatelli *et al.*, 2012).

A short construction schedule limits the financial cost escalation during the construction period. During construction, when no revenues allow the capital repayment, financial interests are compound over a growing invested capital base, increasing exponentially. This is the reason why, assuming the same total overnight construction cost as large units, multiple SMR projects pay lower IDC than LR projects (Carelli *et al.*, 2007b; Boarin *et al.*, 2012).

Shorter PBT of each SMR unit allows to get a cash in-flow from the sale of power generated by early units. Average outstanding capital exposure may be relieved by suitable staggered deployment of successive units, and cash flow from early units may be employed to finance the construction of later units on the site. This capability to self-generate the sources of financing is not available to a single large NPP project and is a valuable option to limit up-front capital requirements: the relevant share of total capital investment cost may be provided by self-financing (Figures 10.15 and 10.16).

SMRs' investment scalability is a key value driver: by staggering the investment effort over time, the average capital-at risk and IDCs are decreased. Cash out-flow profile during the construction phase is smoother for SMRs (Figure 10.17). These features make of SMRs an affordable investment option by investors with financial constraints, despite the conservative assumption of higher total capital investment cost.

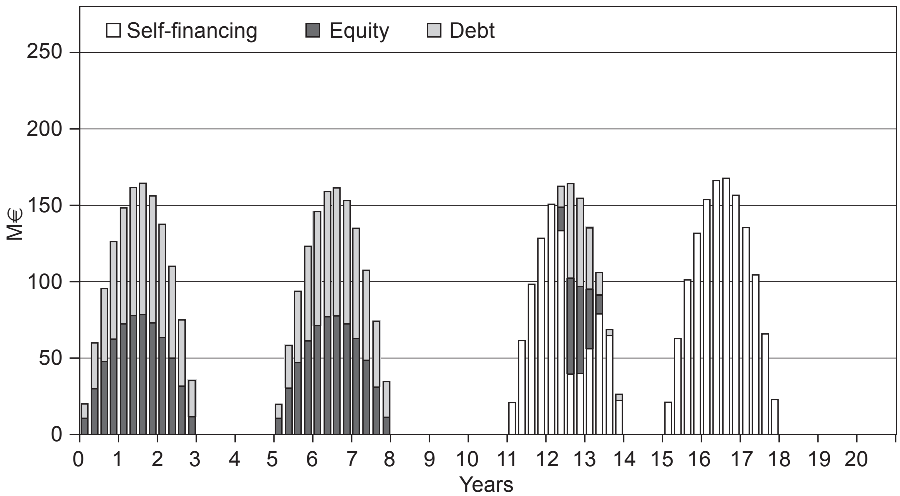

Figure 10.15 Sources of financing for SMRs construction (M€) (Boarin and Ricotti, 2009).

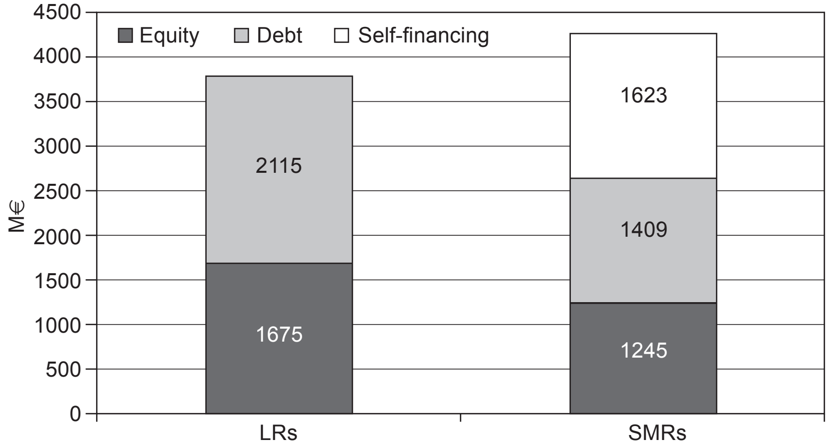

Figure 10.16 Breakdown of total sources of financing (M€) (Boarin and Ricotti, 2009).

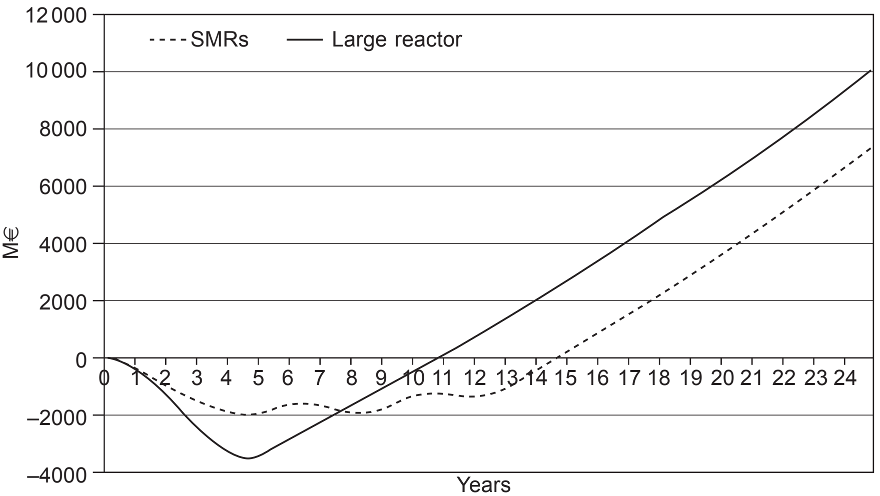

Figure 10.17 Cumulated cash flows of one LR and four equivalent SMR projects (Boarin and Ricotti, 2009).

10.6.2 Introducing uncertainty in the economic analysis

On account of the investment modularization, multiple SMRs offer greater stability in their financial performance, faced with unfavourable boundary conditions: lower average invested capital accounts for lower interest capitalization and lower risk of financial default. All these features are particularly valuable in the so-called 'merchant' scenarios, based on the rules of competition in liberalized electricity and capital markets, and characterized by the high cost of financing. Analysis and simulations in these conditions show that the gap in cost-effectiveness becomes narrower. With a high cost of equity and increasing cost of debt, there is a point where economic performance of SMRs overtakes that of LRs (Figure 10.18), on account of SMRs' capability to limit IDC escalation.

When deterministic and predictable scenarios are considered, assuming the construction schedule is respected, LRs normally show better economic performance based on economy of scale and lower overnight construction costs: PI and IRR are higher and, accordingly, generation cost is lower. But when scenario conditions become stochastic and uncertainties are included in the analysis, multiple SMRs may record higher mean profitability than LRs. In particular, assuming the possibility of a stochastic delay event affecting the construction schedule of both LR and multiple SMR projects, the calculated profitability distribution shows more favourable data dispersion for SMRs toward positive values, meaning that SMRs have a greater chance of performing better in terms of profitability than LRs (Figure 10.19; Boarin and Ricotti, 2011a). A sensitivity analysis on the main economic and financial parameters shows that SMRs have a better capability to perform in changed scenario conditions (Figure 10.20).

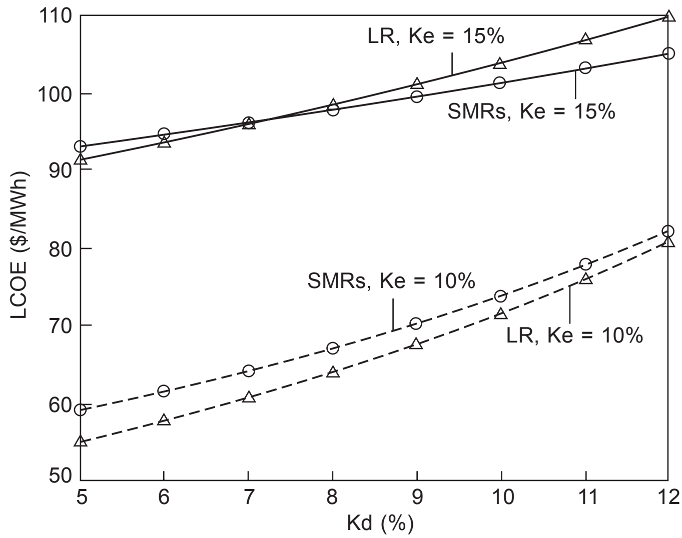

Figure 10.18 Levelized cost of electricity (LCOE) trend at increasing cost of debt Kd, at different cost of equity Ke: 'merchant case' = solid lines; 'supported case' (meaning with risk mitigation strategies and strong public support) = dashed lines (Boarin *et al.*, 2012).

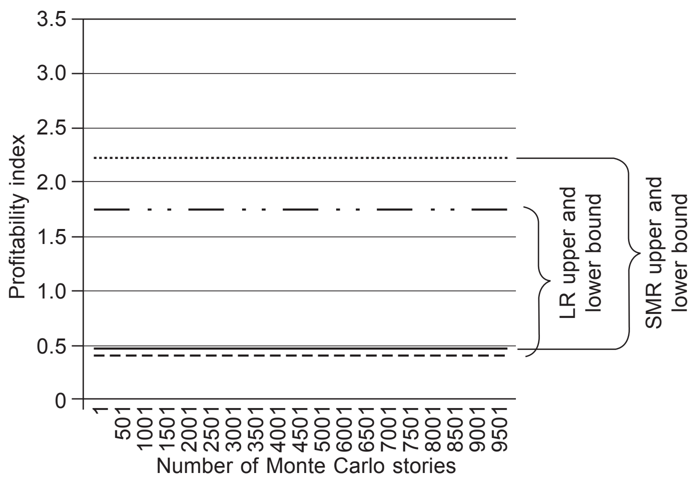

Figure 10.19 Profitability index of one LR vs. four SMRs in stochastic scenario analysis (Monte Carlo simulation, 10 000 stories). Adapted from Boarin and Ricotti (2011a).

10.6.3 SMRs and operating costs

While economic research usually concentrates on capital cost as the dominant driver of the economic competitiveness, operating costs have much lower impact on generation costs. Few estimates are available on SMR O&M costs and fuel costs. Nonetheless some trends and general considerations may be argued:

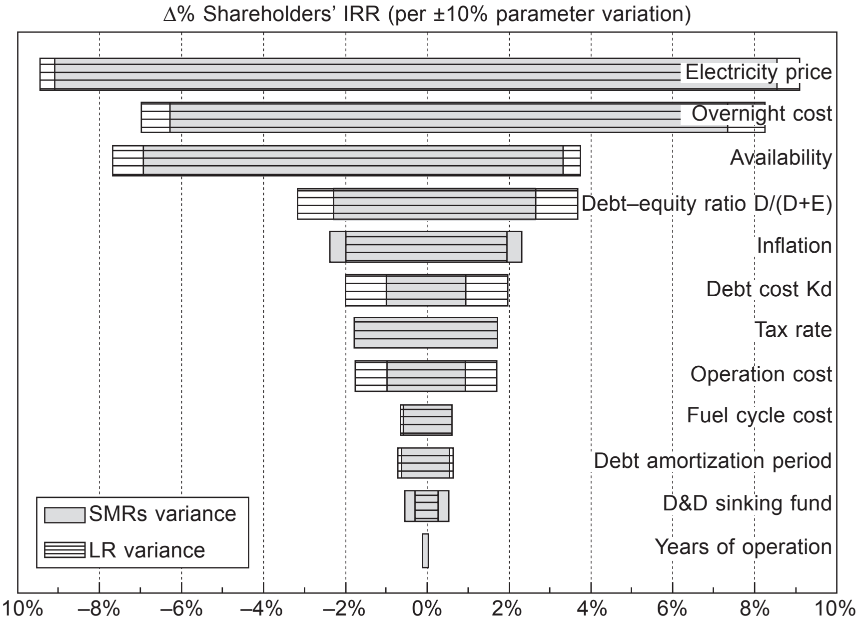

Figure 10.20 Sensitivity of project profitability (IRR) to main parameter input data variation for a merchant case (Boarin *et al.*, 2012).

- The designers of advanced SMRs often indicate that O&M costs might be lower than those of LRs, owing to a stronger reliance of SMRs on passive safety features and to the resulting decrease in the number and complexity of safety features (Kuznetsov and Lokhov, 2011).
- Economy of scale, co-siting economies and learning influence operating costs of multiple SMRs as in the case of construction costs; comparing an LR of 1340 MWe with a fleet of four SMRs of 335 MWe each, the penalty of SMRs on O&M costs due to the loss of economy of scale is mitigated by co-siting and learning effects and the corresponding overall cost increase on LR is limited to +19%; a learning effect on O&M activities of multiple SMRs is also confirmed (Carelli *et al.*, 2008a).
- In general SMRs offer poor neutron economy due to lower reactor core dimensions, which translates into higher fuel cost incidence on generation costs.
- It is expected that long refueling schemes of some SMRs may increase specific fuel costs, due to a less effective fuel utilization, as compared to SMRs with conventional refueling intervals (IAEA, 2006, 2007b).
- Moreover, it is expected that for barge-mounted SMRs the sum of O&M and fuel costs is 50% higher than land-based SMRs, mainly due to a large O&M required by the barge.

Data information on decontamination and decommissioning (D&D) costs of advanced, modular SMR are not available from experience. One possible unbiased way to calculate them is to perform a statistical analysis of the data available from past decommissioning projects. Historical records show that there are several cost drivers that determine the decommissioning cost. Specifically those critical in the comparison between SMR and LR are: plant size, number of units in the site and decommissioning strategy ('immediate decommissioning' or 'deferred decommissioning'). Multiple regression analysis is a powerful tool applicable to these kinds of analysis which is able to quantify exactly the impact of each cost driver; it allows for an in-depth examination of the trend correlation between the dependent and the explanatory variables. The result of this statistical analysis is that the economy of scale also applies to the plant decommissioning activities and represents a disadvantage for SMRs (Locatelli and Mancini, 2010b); the D&D cost for a medium-sized SMR unit may be three times higher than for a large plant. On the other hand, co-siting economies should decrease D&D costs for parallel dismantling of twin units.

It is worth stressing that historical data are related only to GEN I and GEN II reactors (both large and small), not to modern GEN III+ reactors and SMRs. Regarding SMRs, the design layout simplifications and reduced number of components should drive a cost reduction. In the same way as high content of factory fabrication should decrease construction costs by decreasing on-site assembling activities, modular and factory-assembled reactors should be dismantled in a sub-system that could be transported back to a centralized factory, where operations should be cheaper than on-site dismantling (Kuznetsov and Lokhov, 2011; IAEA, 2007b).

As a general, final comment, it can be stated that technical savings from design simplification and standardization and co-siting economies are the competing forces that play against the loss of economy of scale. The balance between these factors should be evaluated on a project-specific basis and supported by data information from actual experience.

10.6.4 Conclusion: the 'economy of multiples'

As seen, multiple SMRs on the same site may be considered as an investment option alternative to a power station based on LRs with the same overall power output. The SMR investment case bears a loss of economy of scale which may be mitigated by some specific cost benefits. These economic benefits, presented in the previous sections, are enhanced by deploying multiple units on a same site. On the construction side, learning accumulation, modularization and co-siting economies are expected to be fostered by the multiple units 'philosophy' and the 'mini-serial production' of a number of smaller and simpler plant units. In addition, design simplification is expected to further contribute to cost-reduction of SMRs, but its evaluation is strictly plant-specific and deserves further analysis and approaches.

On the investment side, the fractioning of total investment into multiple smaller batches may represent a risk mitigation factor against possible cost/time overruns and an opportunity to adapt the investment plan and the power installed rate to the market conditions. All these economic features may be summarized into an 'Economy of Multiple' concept that may counterbalance the 'Economy of Scale' philosophy, especially when uncertainty is introduced in the analysis, affecting market conditions or construction process time schedule.

Some concepts apply to the operating and decommissioning cost as well, with a loss of economy of scale to be partially recovered by the simplification of operating or dismantling procedures. SMR design simplification has a relevant impact both on construction and decommissioning costs and any economic assessment that does not take fully into account such issues tends to be very conservative against SMR.

10.7 Competitiveness of SMRs versus other generation technologies

There are specific niche markets or applications where SMRs are the only applicable option as an NPP. Given their lower capital requirements and small size, which makes them suitable for small electrical grids, SMRs can effectively address the energy needs of small newcomer countries or remote and scattered areas. Their smaller size may better fit co-generation purposes and other energy applications. In these situations, comparison with large units is not applicable. Considering their output size, a 300–400 MWe SMR plant might also be considered as an alternative generation technology to fossil-fueled, base-load small–medium plants, such as coal and combined cycle gas turbine (CCGT).

According to NEA/OECD (2011), nuclear power is generally competitive with many other technologies (coal-fired plants, gas-fired plants, renewables) in Brazil, Japan, Republic of Korea, Russian Federation and the United States. Similarly, some SMRs are expected to be competitive with several projects of coal-fired, gas-fired and renewable plants of various types, including those of small to medium-sized capacity (below 700 MWe). A Monte Carlo analysis comparing SMRs with coal and gas-fired plants (Locatelli and Mancini, 2010a) stresses the fundamental role of the carbon Tax, or the CO_2 sequestration cost, on the competitiveness of nuclear generation cost. Without a carbon tax, coal and CCGT may be more attractive then SMRs, in terms of NPV and LCOE. The carbon tax may dramatically increase the generation cost of coal-fired and CCGT plants and transfer its uncertain value to the overall uncertainty of the investment return of fossil-fueled plants, increasing SMR competitiveness (Figure 10.21).

In the open literature, several studies deal with the application of portfolio theory to power generation sector, but only few compare large and small power plants from this point of view. In Locatelli *et al.* (2011b) and Locatelli and Mancini (2011a) the investigation of the best combinations of base load power plants, for an investor on the basis of different scenarios, is carried out. As far as different Carbon tax and electricity prices are considered, the IRR and the LCOE are calculated using Montecarlo simulations for three base load technologies: nuclear, coal and CCGT. Different plant sizes are considered: for nuclear plants 335 and 1340 MWe, for coal plants 335 and 670 MWe and for CCGT plants 250 and 500 MWe.

Three markets are investigated, referred to as large grid (30 GWe), corresponding to a national-level utility, a medium grid (10 GWe), corresponding to a regional-level utility, and a small grid (2 GWe), corresponding to a municipality or an island. For

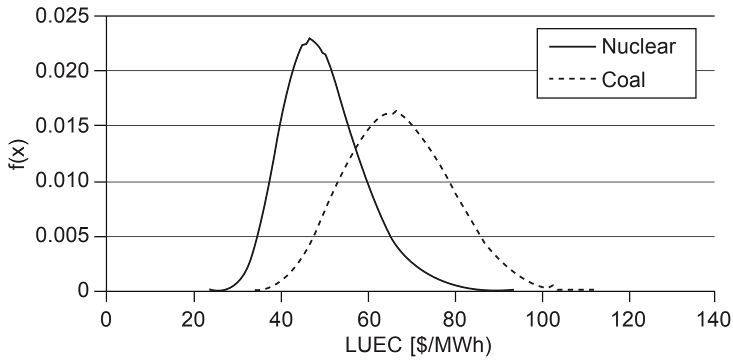

Figure 10.21 Uncertainty introduced by the carbon tax on the coal plant's LCOE (Locatelli and Mancini, 2010a).

each market two types of portfolio are considered: (i) all possible combinations of large plants only and, (ii) small plants combinations only. In both cases the maximum site size is 1340 MWe, i.e. the size of a stand-alone large nuclear power plant, hence economy of scale and economy of multiples are taken into account.

In order to identify the best power plants portfolio mix from the investor point of view, the IRR and LUEC have been assumed as a metric of the investment performance (higher IRR; lower LUEC). The mean value of such indicators, arising from their own specific probability distributions, has been assessed against their respective standard deviation.

The results show that the nuclear power plants play a fundamental role in portfolio generation and become a convenient option when the carbon tax is included in the economic evaluation. Based on the above-mentioned criteria of IRR and LCOE, large plants may represent the best investment option where large new power capacity is required and small plants are competitive when small power installations are required. In order to achieve the highest profitability with the lowest risk, it is necessary to build several plants of different types and, in the case of small grids, this is possible only with small power plants. Although the choices of the investor will be subjected to the specific needs and the risk attitude, guidelines can be drawn to facilitate the selection process:

- large plant portfolios usually have better performance than small plant portfolios according to the LCOE indicator;
- small plant portfolios may have comparable performance with respect to large plant portfolios, according to the IRR indicator;
- in case of large markets (> 10 GWe), large plant portfolios are the best alternative in most cases;
- in the case of small size markets (2 GWe), small plant portfolios are able to provide a lower investment risk than large plant portfolios for both IRR and LCOE indicators;
- the optimal mix is largely made up with nuclear power plants when a medium/high cost of CO_2 emissions or a low electricity price apply;
- in the absence of a carbon tax, the best performances are provided by coal-fired plants;

- an increase in the electricity price or a reduction of the carbon tax decreases the gap between the small and the large plant efficiency frontiers.

10.8 External factors

The analysis of other non-design or even non-technological features (external factors) may have a tremendous impact on the deployment strategy of SMRs. An 'external factor' is a factor usually not monetary and not directly considered within the investment evaluation, because it is not under the direct control of the investor. However it may strongly influence the life cycle and the attractiveness and the feasibility of the project itself. These external factors (Figure 10.22), such as security of fuel supply, public acceptance and environmental aspects, have been tentatively clustered and investigated (Mancini *et al.*, 2009; Locatelli and Mancini, 2011b).

The preliminary results indicate that SMRs may better fit all the factors. However it is important to point out that the 'not in my back yard' (NIMBY) syndrome limits the possibility of spreading SMRs in different sites, to exploit the advantages of a decentralized generation model like better grid stability. Therefore, a plausible scenario for many countries is the concentration of multiple SMRs in each site. Even in this configuration, the SMRs should reap many advantages through all the life cycle. During the planning and construction phases, more sites than for LRs can be exploited because more sites are suitable to SMR deployment; SMR time-to-market is shorter, and fewer risks are associated to the construction phase as well as increased benefits for local industries. In the operation phase, SMRs provide more job positions and do not require additional costs in terms of 'spinning reserves'.

The external factors could be integrated with the monetary factors to perform a holistic evaluation, through a six-step methodology (Locatelli and Mancini, 2012b):

1. Identification of relevant attributes for evaluation and selection, looking at the specific country taken into consideration.
2. Definition of measurement and evaluation process of each attribute (quantitative or qualitative, monetary or not, etc); each NPP design has to be evaluated on each attribute.
3. Definition of attribute's hierarchical structure as required by a fuzzy analytical hierarchy process (AHP) application.
4. Expert elicitation to get attribute weights; each expert has to fill in a questionnaire of pairwise comparisons between attributes or groups of them. Fuzzy AHP permits judgements through linguistic variables (Yang and Chen, 2004).
5. Pairwise comparison matrices from different decision makers are aggregated through the geometric mean method presented in Kuo *et al.* (2002). Buckley's method (Buckley, 1985) is then applied to the hierarchical structure and to get final attributes weights; these are fuzzy sets, so a decoding process is needed to obtain crisp values, the most common being the centroid method (Opricovic and Tzeng, 2004).
6. The TOPSIS method is applied for the final integration, looking at the five steps in Opricovic and Tzeng (2004).

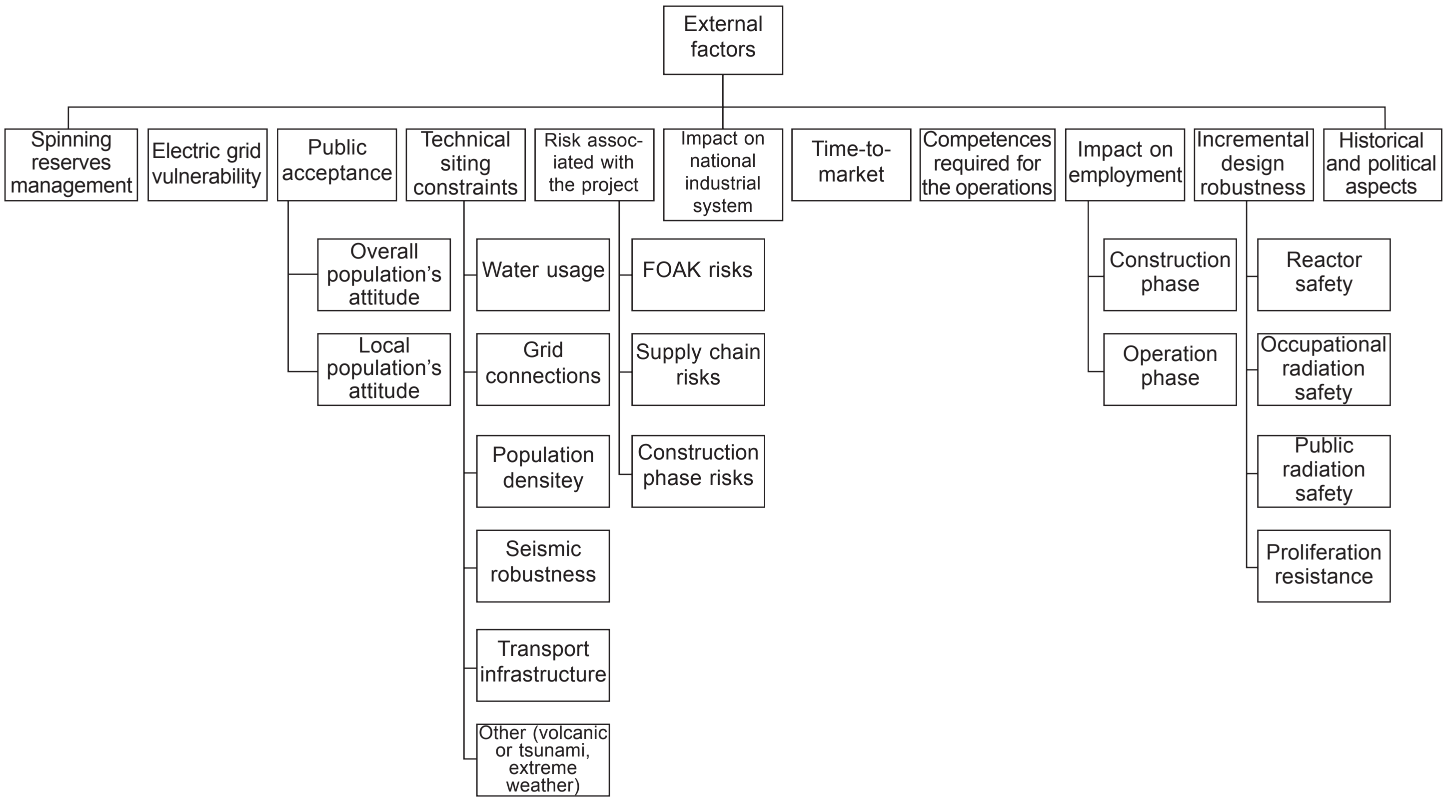

Figure 10.22 External factors to be considered in the comparison between LRs and SMRs.

10.9 Future trends

Most of the SMR projects are not a mere scaling of LRs, exploiting original design features. Several of them are still in the design phase and are conceived with a deployment strategy that benefits from investment modularity.

In the current developing phase of SMR concepts, due investigation of the potential, positive features is required and some complementary research efforts are needed. As far as SMR economic, financial and deployment issues are concerned, the main R&D efforts should be focused on the cost estimation (bottom-up approach) and on the estimation of the deployment flexibility value (by means of the real options analysis).

- *Bottom-up approach:* a more robust cost estimation is needed, with specific focus on design-based economies and enhancements, along with the SMR design development and more details on the structures, systems, components, layout, etc. A bottom-up approach is a suitable, alternative methodology to a similarity-based top-down approach, to estimate and assess construction costs. O&M costs should also be included, once the SMR operating strategy and related licensing issues are addressed and known, e.g. referring to crew requirements and multiple SMR modules operated by a single control room.
- *Real options:* the application of this methodology, complementary to the DCF analysis, is able to catch the value of the investment flexibility. This approach perfectly fits the modularity features of SMRs. Modular investments give the opportunity to delay, anticipate, stop or accelerate the deployment plan, according to the time evolution of the boundary conditions for the business, given, for example, by the energy market, the regulatory framework, the political as well as the macro-economic environment. This opportunity is valuable as direct cash inflows and should be taken into account to get a correct evaluation of the SMRs investment.

Real options are the most suitable tool to evaluate the economic potential of co-generation of non-electric products. Co-generation may be used as an option to adapt the SMR's power generation to the load curve without losing economic value from the nuclear investment and without stressing the primary loop thermo-mechanics. Intrinsic modularity of multiple SMRs is particularly suitable to enhance the overall site generation flexibility, by devoting the thermal power generated by some SMR units to the co-generation processes.

10.10 Sources of further information and advice

Blyth, W., 2006. *Factoring risk into investment decisions*, working paper, UK Energy Research Centre, London.

Bowers, H.I., Fuller, L.C. and Myers, M.L., 1983. *Trends in Nuclear Power Plant Capital Investment Cost Estimates 1976 to 1982*, A.2. Summary of Literature Review of Cost-Size Scaling of Steam-Electric Power Plants. ORNL/TM-8898. Oak Ridge National Laboratory, TN, USA.

Bowers, H.I., Fuller, L.C. and Myers, M.L., 1987. *Cost Estimating Relationships for Nuclear Power Plant Operation and Maintenance*. ORNL/TM-10563. Oak Ridge National Laboratory, TN, USA.

Carayannis, E.G., 1996. Re-engineering high risk, high complexity industries through multiple level technological learning. A case study of the world nuclear power industry. *Journal of Engineering and Technology Management*, **12** (4), 301–318.

David, P.A. and Rothwell, G.S., 1996. Measuring standardization: an application to the American and French nuclear power industries. *European Journal of Political Economy*, **12** (2), 291–308.

David, P.A. and Rothwell, G.S., 1996. Standardization, diversity and learning: strategies for the coevolution of technology and industrial capacity. *International Journal of Industrial Organization*, **14** (2), 181–201.

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

Finon, D. and Roques, F., 2008. *Contractual and Financing Arrangements for New Nuclear Investment in Liberalised Markets: Which Efficient Combination?*, CeSSA Working Paper, European Regulation Forum on Supply Activities.

Gollier, C., Proul, D., Thais, F. and Walgenwitz, G., 2005. Choice of nuclear power investments under price uncertainty: valuing modularity. *Energy Economics*, **27**, 665–685.

Ingersoll, D.T., 2009. Deliberately small reactors and the second nuclear era. Progress in *Nuclear Energy*, **51**, 589–603.

Kazachkovskii, O.D., 2001. Calculation of the economic parameters of a nuclear power plant. *Atomic Energy*, **90** (4), 329–336.

Kennedy, D., 2007. New nuclear power generation in the UK: cost benefit analysis. Energy Policy, **35**, 3701–3716.

Koomey, J. and Hultmanc, N.E., 2007. A reactor-level analysis of busbar costs for US nuclear plants, 1970–2005. *Energy Policy*, **35**, 11, 5630.

Krautmann, A. and Solow, J.L., 1988. Economies of scale in nuclear power generation. *Southern Economic Journal*, **55**, 70–85.

Langlois, R.N., 2002. Modularity in technology and organization. *Journal of Economic Behavior and Organization*, **49**, 19–37.

Lapp, C.W. and Golay, M.W., 1997. Modular design and construction techniques for nuclear power plants. *Nuclear Engineering and Design*, **172**, 327–349.

Marshall, J.M. and Navarro, P., 1991. Costs of nuclear power plant construction: theory and new evidence. *RAND Journal of Economics*, **22** (1), 148–154.

Oxera, 2005. Financing the Nuclear Option: Modeling the Cost of New Build. In *Agenda: advancing economics in business*, www.oxera.com.

Phung, D.L., 1987. *Theory and Evidence for Using the Economy-of-Scale Law in Power Plant Economics*. ORNL/TM-10195. Oak Ridge National Laboratory, Oak Ridge, TN, USA.

Reid, L., 2003. *Modeling Modularity Impacts on Nuclear Power Plant Costs*, ORNL, Oak Ridge, TN.

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

Schock, R.N., Brown, N.W. and Smith, C.F., 2001. *Nuclear Power, Small Nuclear Technology, and the Role of Technical Innovation: an Assessment*. Working paper for the Baker Energy Forum. Rice University, Houston, TX.

Takizawa, S. and Suzuki, A., 2004. Analysis of the decision to invest for constructing a nuclear power plant under regulation of electricity price. *Decision Support Systems*, **37**, 449–456.

Toth, F.L. and Rogner, H.-H., 2006. Oil and nuclear power: past, present, and future. *Energy Economics*, **28**, 1–25.

References

Barenghi, S., Boarin, S. and Ricotti, M.E., 2012. *Investment in Different Sized SMRs: Economic Evaluation of Stochastic Scenarios by INCAS Code*. Proceedings of ICAPP'12, paper 12322, Chicago.

Barkatullah, N., 2011. Possible Financing Schemes for Current and Near Term Nuclear Power Project, Workshop on Technology Assessment of Small and Medium-sized Reactors for Near Term Deployment, IAEA-PESS. http://www.iaea.org/NuclearPower/Downloadable/Meetings/2011/2011-12-05-12-09-WS-NPTD/Day-4/23_IAEA_Barkatullah-Economics_SMRDec2011.pdf (accessed Aug. 2013).

Binz, R., Sedano, R., Furey, D. and Mullen, D., 2012. Practicing Risk-Aware Electricity Regulation: What Every State Regulator Needs to Know, CERES Report, Ronald J. Binz Public Policy Consulting.

Boarin, S. and Ricotti, M.E., 2009. *Cost and Profitability Analysis of Modular SMRs in Different Deployment Scenarios*. Proceedings of the 17th Int. Conf. on Nuclear Engineering – ICONE17, paper 75741, Brussels.

Boarin, S. and Ricotti, M.E., 2011a. *Risk Analysis of Nuclear Power Investments in Large Versus Small–Medium Sized Reactors*, Proceedings of Nuclear Power Europe, paper 1545, Milan.

Boarin, S. and Ricotti, M.E., 2011b. *Multiple Nuclear Power Plants Investment Scenarios: Economy of Multiples and Economy of Scale Impact on Different Plant Sizes*. Proceedings of ICAPP 2011, paper 11193, Nice.

Boarin, S., Locatelli, G., Mancini, M. and Ricotti, M.E., 2012. Financial case studies on small–medium sized modular reactors. *Nuclear Technology*, **178** (2) 218–232.

Buckley, J.J., 1985. Ranking alternatives using fuzzy numbers. *Fuzzy Sets and Systems*, **15**, 1-31.

Carelli, M.D., Petrovic, B., Mycoff, C.W., Trucco, P., Ricotti, M.E. and Locatelli, G., 2007a. *Economic Comparison of Different Size Nuclear Reactors*. Proceedings of LAS/ANS Symposium, Cancun, Mexico.

Carelli, M.D., Petrovic, B., Mycoff, C.W., Trucco, P., Ricotti, M.E. and Locatelli, G., 2007b. *Smaller Sized Reactors can be Economically Attractive*. Proceedings of ICAPP 2007, Paper 7569, Nice.

Carelli, M.D., Mycoff, C.W., Garrone, P., Locatelli, G., Mancini, M., Ricotti, M.E., Trianni, A. and Trucco, P., 2008a. *Competitiveness of Small-medium, New Generation Reactors:*

A Comparative Study on Capital and O&M costs. Proceedings of 16th Int. Conf. on Nuclear Engineering-ICONE 16, Paper 48931. Orlando, FL., ASME.

Carelli, M.D., Garrone, P., Locatelli, G., Mancini, M., Trucco, P. and Ricotti, M.E., 2008b. Chap.6. Nuclear Renaissance: An Assessment of Small–Medium, Integrated and Modular plants. In *Investments and Service Quality in the Electricity Industry*, Garrone P. (Ed.), Franco Angeli.

Carelli, M.D., Garrone, P., Locatelli, G., Mancini, M., Mycoff, M., Trucco, P. and Ricotti, M.E., 2010. Economic features of integral, modular, small-to-medium size reactors. *Progress in Nuclear Energy*, **52**, 403–414.

Chu, S., 2010. *The Wall Street Journal*, March 23.

Damodaran, A., 2011. Chap.3 *The Basics of Risk*, in Applied Corporate Finance, 3rd edition, John Wiley & Sons.

DOE, 2005. *Electric Power Annual 2005*, DOE/EIA-0348.

Dolley, S., 2008. Options available to lessen risk of nuclear investing, analysts say, *Nucleonics Week*, **49**, 47.

EMWG, 2007. Economic Modeling Working Group – Cost Estimating guidelines for generation IV nuclear energy systems, Revision 4.2. GIF/EMWG/2007/004, OECD. http://www.gen-4.org/Technology/horizontal/EMWG_Guidelines.pdf (accessed Aug. 2013).

Flyvbjerg, B., Bruzelius, N. and Rothengatter, W., 2003. *Megaprojects and Risk: An Anatomy of Ambition*. Cambridge University Press.

Frischtak, C.R., 1994. Learning and technical progress in the commuter aircraft industry: an analysis of Embraer's experience. *Research Policy*, **23** (5), 601–612.

Gallanti, M. and Parozzi, F., 2006. Valutazione dei costi di produzione dell'energia elettrica da nucleare. *Energia*, **3**, 60–70.

Goldberg, S. and Rosner, R., 2011. Small Modular Reactors – Key to Future Nuclear Power Generation in the U.S., Energy Policy Institute at Chicago, The Harris School of Public Policy Studies. http://epic.uchicago.edu/i/publication/SMR_Final_White_Paper_7-11.pdf (accessed Aug. 2013).

Grubler, A., 2010. The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy*, **38**, 5174–5188.

Hayns, M.R. and Shepherd, J., 1991. SIR reducing size can reduce cost. *Nuclear Energy*, **30**, (2), 85–93.

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

IAEA, 2007a. Safety glossary–Terminology used in nuclear safety and radiation protection. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1290_web.pdf (accessed Aug. 2013).

IAEA, 2007b. Status of Small Reactor Designs Without On-Site Refuelling. IAEA-TECDOC-1536. http://www-pub.iaea.org/MTCD/Publications/PDF/te_1536_web.pdf (accessed Aug. 2013).

Kessides, I.N., 2012. The future of the nuclear industry reconsidered: risks, uncertainties, and continued promise, *Energy Policy*, **48**, 185–208.

Kuo, R.J., Chi, S.C. and Kao, S.S., 2002. A decision support system for selecting convenience store location through integration of fuzzy AHP and artificial neural networks. *Computers in Industry*, **47**, 199–214.

Kuznetsov, V. and Lokhov, A., 2011. Current Status, Technical Feasibility and Economics of Small Nuclear Reactors. OECD-Nuclear Energy Agency, Paris. http://www.oecd-nea.org/ndd/reports/2011/current-status-small-reactors.pdf (accessed Aug. 2013).

Locatelli, G. and Mancini, M., 2010a. Small–medium sized nuclear coal and gas power plant:

A probabilistic analysis of their financial performances and influence of CO_2 cost. *Energy Policy*, **10** (38), 6360–6374.

Locatelli, G. and Mancini, M., 2010b. Competitiveness of small-medium, new generation reactors: a comparative study on decommissioning. *Journal of Engineering for Gas Turbines and Power*, **10** (132), 102906.

Locatelli, G. and Mancini, M., 2011a. Large and small baseload power plants: Drivers to define the optimal portfolios. *Energy Policy*, **39** (12), 7762–7775.

Locatelli, G. and Mancini, M., 2011b. The role of the reactor size for an investment in the nuclear sector: An evaluation of not financial parameters. *Progress in Nuclear Energy*, **53** (2) 212–222.

Locatelli, G. and Mancini, M., 2012a. Looking back to see the future: Building nuclear power plants in Europe. *Construction Management and Economics*, **30**, 623–637.

Locatelli, G. and Mancini, M., 2012b. A framework for the selection of the right nuclear power plant. *International Journal of Production Research*, **50** (17), 4753–4766.

Locatelli, G., Mancini, M. and Vannucci, C., 2011a. *How the Plant Size Impacts on Project Risks: The Nuclear Power Reactors Case Study*. Proceedings of IPMA-25th World Congress, Brisbane, Queensland.

Locatelli, G., Mancini, M. and Agosti, D., 2011b. *Nuclear Power Plants in the Base Load Generation Portfolios: A Probabilistic Study of the Size Role*. International Congress on Advances in Nuclear Power Plants - ICAPP 2011.

Locatelli, G., Mancini, M., Ruiz, F. and Solana, D., 2012. *Using Real Options to Evaluate the Flexibility in the Deployment of SMR*. Proceedings of ICAPP'12, paper 12233, Chicago.

Lovins, A.B., 1986. The origins of the nuclear fiasco. *The Politics of Energy Research and Development*, Byrne J., Rich D. (Eds), Transaction Books, pp. 7–34.

MacKerron, G. *et al*., 2005. Paper 4 – Economics of Nuclear Power: A Report to the Sustainable Development Commission, University of Sussex. http://www.sd-commission.org.uk/data/files/publications/Nuclear-paper4-Economics.pdf (accessed Aug. 2013).

Mancini, M., Locatelli, G. and Tammaro, S., 2009. *Impact of the External Factors in the Nuclear Field: A Comparison Between Small Medium Reactors vs. Large Reactors*. Proceedings of the 17th Int. Conf. on Nuclear Engineering-ICONE 17, paper 75689, Brussels.

Matzie, R.A., 2005. Building New Nuclear Plants to Cost and Schedule – An International Perspective, Royal Academy of Engineering, Energy Seminars. http://www.raeng.org.uk/events/pdf/archive/Energy_Seminars_Nuclear_Fission_Regis_Matzie.pdf (accessed Aug. 2013).

NEA/OECD, 2011. Current Status, Technical Feasibility and Economics of Small Nuclear Reactors. http://www.oecd-nea.org.

Opricovic, S. and Tzeng, G.H., 2004. Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *European Journal of Operational Research*, **156**, 445–455.

OTA – U.S. Congress, Office of Technology Assessment, 1993. Aging Nuclear Power Plants: Managing Plant Life and Decommissioning, OTA-E-575, Washington, DC. http://www.fas.org/sgp/othergov/doe/lanl/lib-www/ota/00418532.pdf (accessed Aug. 2013).

Parsons, J.E. and Du, Y., 2009. Update on the Cost of Nuclear Power, MIT-CEEPR. http://web.mit.edu/ceepr/www/publications/workingpapers/2009-004.pdf (accessed Aug. 2013).

Sullivan, G.P., Pugh, R., Melendez, A.P. and Hunt, W.D., 2010. Operations & Maintenance Best Practices – A Guide to Achieving Operational Efficiency. Pacific Northwest National Laboratory. http://www1.eere.energy.gov/femp/pdfs/OandM.pdf (accessed Aug 2013)

Williams, K.A. and Miller, K., 2006. A User's Guide for G4 – ECONS: a Generic EXCELbased Model for Computation of the Projected Levelized Unit Electricity Cost (LUEC) from Generation IV Reactor Systems. Generation IV International Forum.

Wright, T.P., 1936. Factors Affecting the Cost of Airplanes. *Journal of the Aeronautical Sciences*, **3** (4), 122–128.

Yang, C.C. and Chen, B.S., 2004. Key quality performance evaluation using fuzzy AHP. *Journal of the Chinese Institute of Industrial Engineers*, **21** (6), 543–550.