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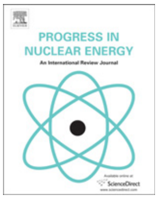

Economic features of integral, modular, small-to-medium size reactors

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ABSTRACT

The renewed interest towards nuclear energy is largely based on the escalation of fossil fuels prices and the global warming concerns. The nuclear option has to face not only the public opinion sensibility, mainly related to plant safety and waste disposal issues, but also the economic evaluation from investors and utilities, particularly careful on that energy source and in deregulated markets. Smaller size nuclear reactors (IAEA defines as "small" those reactors with power<300 MWe and "medium" with power<700 MWe) can represent a viable solution for both the stakeholders, especially for developing countries, or countries with not-highly-infrastructured and interconnected grids, or even for developed countries when limitation on capital at risk applies. A description of Small-Medium size Reactor (SMR) economic features is presented, in a comparison with the state-of-the-art Large size Reactors. A preliminary evaluation of the capital and O&M costs shows that the negative effects of the economies of scale can be balanced by the integral and modular design strategy of SMRs.

1. Introduction

In the recent years, the growing and renewed interest in the exploitation of nuclear energy has been mainly driven by the escalation of fossil fuels prices and the global warming concerns, being the nuclear energy virtually free from CO_2 and greenhouse gases emissions. That essentially has led to the construction of new Nuclear Power Plants (NPPs) even in the western world after at least a couple of decades, and to the planning of several hundreds of NPPs during the next ones, to concur in fulfilling the future global energy needs.

Besides the safety of the nuclear plants and the environmental impact of the nuclear waste, the economics of the nuclear energy is one of the key drivers in both the public opinion and the experts' analysis on the viability and acceptability of the nuclear option. Studies have been recently carried out on energy scenarios explicitly including nuclear (e.g. in Toth and Rogner, 2006), and the economic and investment issues have been addressed by several Authors, as in Kazachkovskii (2001), Kennedy (2007), Takizawa and Suzuki (2004), Yoo and Yoo (2009).

The interest in the nuclear energy source is coming not only from the so-called developed countries, but also from those belonging to the emerging economies. However, especially in the latter ones some context or market conditions can limit the adoption of NPPs when usually framed into Large size Reactors (LRs), e.g. i) electrical grids with limited capacity, where power variations in excess of 10% of the total grid capacity can endanger grid operation and stability; ii) remote areas requiring smaller, localised power centers, to avoid long and expensive transmission lines; iii) a geography and demography featuring mid-size urban and power needing areas fairly scattered, rather than concentrated in a few "metropolitan areas"; iv) financial capabilities which preclude raising the huge capitals required by LRs; v) the need for cogeneration (i.e. desalination, district heating, industrial steam) – although in principle cogeneration is independent on the size of the NPP, in practice economic considerations have driven the LRs to be essentially pure electricity producers.

To overcome these constraints, the adoption of Small-Medium size Reactors (SMRs) is proposed as a viable solution (Ingersoll, 2009). As an example, the US-DOE led, Global Nuclear Energy Partnership (GNEP, 2007) initiative, currently participated by 20 countries, has identified the development of "Grid-Appropriate Reactors" as an implementing element, needed to enable worldwide expansion of the peaceful use of nuclear power.

Several SMR designs (Bae et al., 2001; Carelli et al., 2004; Fukami and Santecchia, 2000; Hibi et al., 2004; Ueda, 2005) are currently at different stages of development throughout the world and interest in their deployment has been expressed as well. SMRs usually have

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Nomenclature

D&D	Decontamination and Decommissioning
FOAK	First-Of-A-Kind
IRIS	International Reactor Innovative and Secure
LR	Large size Reactor
LUEC	Levelized Unit Electricity Cost
NOAK	Nth-of-a-kind
NPP	Nuclear Power Plant
O&M	Operation and Maintenance
SMR	Small-Medium size Reactor
WACC	Weighted Average Cost of Capital

attractive characteristics of simplicity, enhanced safety and require limited financial resources. On the other side, they are not considered as economically competitive with LRs because of the accepted axiom and a misguided application of the Economies of Scale principle. The specific capital cost (currency/KWe) of a nuclear reactor decreases with size, due to the rate reduction of unique set-up costs in investment activities (e.g. siting activities, or civil works to access the transmission network), the more efficient use of raw materials and the exploitation of higher performances characterizing larger equipments (e.g. steam generators, heat exchangers, pumps, etc.). Thus, when the size and the power increase, in the specific capital cost expression the numerator (currency) increases less than the denominator (KWe). Consequently, in large developed countries, during last four decades, the reactor size has steadily increased from a few hundred MWe to 1500 MWe and more today.

But, the economies of scale apply only if the reactors are of a very similar design, as it has been the case in the past. This is no longer true today, where smaller, modular reactors have very different designs and characteristics from the large ones. Thus, assuming by definition that, because of the economies of scale principle, the capital cost of a smaller size reactor is higher than for a large size reactor is simplistic and wrong. The awareness and realization of the economic potential of SMRs has grown significantly in the last few years, since the seminal paper from Shepherd and Hayns (1991), and several works have pointed the attention also on the economic features arising from small-medium size including their simplicity and modularity (Lapp and Golay, 1997; Afanasiev et al., 1997; Tian, 2001; Zrodnikov et al., 2006; Mitenkov et al., 2007; Zhang and Sun, 2007).

In addition to individual studies, the IAEA has launched in 2006 a collaborative project to address the competitiveness of SMRs. IAEA defines as "small" those reactors with power <300 MWe and "medium" with power <700 MWe. The paper refers mainly to the results of the study carried out in that frame. In the paper, the IRIS reactor is used as an example for small, modular reactors, but the analysis and conclusions are applicable to the whole spectrum of SMRs. A description of Small-Medium size Reactor (SMR) economic features is presented, in a comparison with the state-of-the-art Large size Reactors.

2. Economic characterization of SMRs

Economies of scale are widely held to drive the generation cost structure of nuclear power plants (Krautmann and Solow, 1988; Phung, 1987). Traditional techno-economic analyses show that the average investment and operating costs per unit of electricity are decreasing with respect to increasing plant size. Yet this result cannot be directly transferred into the investment analyses of SMRs versus LRs, because it relies upon the clause "other things being equal". In other words, it assumes that SMRs are the same as LRs except for size. On the contrary, SMRs exhibit several benefits that are uniquely available to smaller innovative reactors and can only to a very limited extent be replicated by LRs. The differential benefits of SMRs are reviewed, among others, by Shepherd and Hayns (1991), Schock et al. (2001) and Miller (2005).

Once the economies of scale have been modelled, as in each case of comparison depending on the level of detail of the analysis, the several differential SMR features have to be explored and modelled as drivers of the economic and financial performances of SMRs vs. LRs.

Indeed the wide spectrum of factors that differentiates the competitiveness of SMRs vs. LRs is twofold:

- Factors which are applicable to SMRs only or are critically affected by the difference in design and approach brought in by the SMRs (SMR *ad hoc* factors);
- Factors which affect SMRs and large plants in a comparable way (*common* factors). Even for the common factors, a comparative quantitative evaluation might not be straightforward.

Those *ad hoc* and the *common* factors are qualitatively discussed in the following sections. Presented here are the ones judged to have higher priority for a quantitative evaluation. The list of factors considered (Table 1) is by no means exhaustive and others might be considered, furthermore there is a degree of arbitrariness in the distinction between *ad hoc* and *common* factors.

2.1. SMR ad hoc factors

2.1.1. Investment scalability

Investments in SMRs are inherently modular: due to smaller sizes and shorter construction times, the capacity additions of SMRs are more flexible in sizing, timing and siting than those of LRs. In particular, the plant capacity is more readily adaptable to changing market conditions. This has far-reaching implications for generation costs, revenues and financial costs. Due to shorter construction times, the investment timing of SMRs can be postponed closer to the planned operation date (investment deferral), without any reduction of installed capacity or revenue loss. The shorter the SMR construction time, the higher the net present value of investment. For a given size, the multiple SMRs have lower financial costs than a single LR. Alternatively, if the demand is known to grow at a sufficiently high rate, investments in SMR units can be sequenced (the last installed SMRs unit has the same operating date as LR) or concentrated (parallel construction resulting in an earlier operation date than LRs) (market matching). Here the financial costs related to the deployment of SMR units may

Table 1
List of differential factors in the competitiveness evalution of SMRs vs LRs.

SMR *ad hoc* (specific) factors	*Common* factors
Design-related characteristics (*)	Size (*)
Compactness	Modularization
Cogeneration	Factory fabrication
Match of supply to demand (*)	Multiple units at a single site (*)
Reduction in planning margin	Learning (*)
Grid stability	Construction time (*)
Economy of replication	Required front end investment
Bulk ordering	Progressive construction/operation of multiple modules
Serial fabrication of components	

Note: those listed by (*) have been quantitatively evaluated in the paper.

be comparable to or worse than LRs, but revenues are earlier and larger, therefore for a given size, the multiple SMRs allow to reap revenues that would be foregone by a LR.

2.1.2. *Investment flexibility*

Whereas market conditions are relatively "certain" (i.e. the trends of the electricity price and demand are steady and, thus, can be relied upon for long-term planning), the SMR modularity translates in scalability. In contrast, whereas market conditions are highly uncertain, the SMR modularity translates in adaptability, which is an extreme form of temporal and spatial flexibility in the plant deployment. Such a "reversible" nature of investment in SMR units is apparent when one focuses upon the market risks related to LR investment (Gollier et al., 2005). The LR adopters have to cope with upward (or downward) swings of price and demand or localised increase (or decrease) of demand by the means of long-term planning, given the LR long lead times. Since the event is at the best known in likelihood, both the decision to invest and the decision not to invest may prove to be inefficient. A large share of invested capital may result to be sunk (idle), or consistent revenues may be foregone: the economic risk of LR investment is greater because is greater, for a certain period of time, the "sunk" portion of invested capital.

Due to shorter lead times and smaller size, SMRs allow the investors to more closely and quickly adapt to early signals of changing market conditions. The shorter lead times of SMRs allow to split investments for additional units in a closer proximity to the market evolution (electrical load – market matching under uncertainty). In comparison, the LR investment may result in an expected loss of revenues with respect to SMRs for power not taken.

The latter effect translates in a higher net present value, which emerges for any given cost of capital. Yet an additional effect of temporal and spatial flexibility of deployment is related to a lower cost of capital due to a perception of reduced risk by both creditors and shareholders. They are aware that investments in SMR units are more capable to match the new market conditions; i.e. they are less exposed to market uncertainty than LR investment, other things being equal. Accordingly, they demand a lower risk premium to invest in the project (reduced risk premium). For a given size, the multiple SMRs might have lower financial costs than LR.

2.1.3. *Easier plant-grid matching*

Not only the economic and financial requirements have to be matched to provide a suitable product for the energy market. An important technical requirement comes from the power grid and its stability. Some developed countries and areas, as the western European Union, are well interconnected and can sustain even large power stations. Historically, the requirements of large national markets with big power grids have driven the development of nuclear power reactors, resulting in commercial units of 1000 MWe and more. On the other side several countries, even in the EU, have much smaller grids and less well-developed technical infrastructures. These grids are not able to accept the connection of concentrated, large power stations. This represents a limit that can technically prevent an efficient use of LRs. A SMR design approach, tailored to this market segment, could help meeting the rising power demands associated with economic growth and urbanization, while avoiding grid instability concerns; the use of fossil fuels and related greenhouse concerns, at the same time. Therefore for a given size the multiple SMR allows to reap profits that would be lost by a LR.

2.1.4. *New design strategy and solutions*

Even the technological choices on the design phase can directly affects the economics of NPPs. An integral and modular approach to the design of the nuclear reactors offers the unique possibility to exploit a simplification of the plant. This can lead to a reduction of the type and number of components. As an example, the complete integration of all the primary components inside the Reactor Pressure Vessel (RPV) reached by IRIS design (Carelli et al., 2004) avoids large, high pressure piping. This positively affects also the safety of the plant, allowing a dramatic increase of the safety level, via a reduction of the number of safety systems and a simplification of the remaining ones. The integration concept increases also the compactness of the plant (volume over power ratio), with a reduction of the containment volume. A further positive effect is that also the security of the NPP is improved, with a small imprinting of the plant on the ground and a limited area of its skyline, leading e.g. to a reduction of terrorist air attack probability. Moreover, the plant lifetime can be increased and the plant quality of performance kept all along its lifetime, since e.g. radiation damage on the RPV is practically avoided by the inherent shielding provided by the large water thickness between the RPV and the core. Considering all these aspects, for a given size, the multiple SMRs option might decrease the Levelized Unit Electricity Cost (LUEC).

2.1.5. *Cogeneration*

Besides electricity, other products can be obtained by SMRs. Part of the heat generated by the nuclear reactor can be used for urban heating or desalination process (Tewari and Rao, 2002; Tian, 2001). This is obtained with a sensible reduction of the heat to be rejected to the environment, as usually required by the Rankine thermal cycle in the heat-to-electricity conversion process. A technical requirement is to locate the heat or the desalination plant near the end-user areas. The SMRs increased safety level and the reduced radiation source term can lead to a reduction of the emergency planning zone hence to locate the SMRs not far from the urban areas. Moreover the thermal power available from a SMR for non-electricity products is coherent with the thermal load or water needs of an urban area. These aspects dramatically increase the possibilities for SMRs, compared to the LRs, of deploying cogeneration plants. Therefore, for a given size, the SMRs allow to reap profits that would be lost by a LR.

2.1.6. *Mass production economies*

For a certain installed power many more SMRs than LRs are required since the power provided by an SMR is a fraction of the power provided by a LR. Therefore it is possible having a heat bulk ordering process of components (e.g. valves). This aspect allows the SMRs to achieve the mass production economies and a more standardized procurement process.

2.2. *Common factors*

2.2.1. *Plant size*

The size of a NPP is the first and most obvious of the common factors which, of course, generates the economies of scale. If the design is only marginally different, the specific capital cost of a larger unit is significantly lower than for a smaller version.

2.2.2. *Modularization*

Generation IV International Forum (GIF), a framework for international cooperation in research and development for the next generation of nuclear energy systems, defines "modularization like" the process of converting the design and construction of a monolithic plant or stickbuilt scope to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies (EMWG, 2005). It is well known that the factory fabrication is cheaper than the site fabrication, but the limit is the possibility of a cheap shipping of the modules built to the site. The SMRs can take a differential advantage since it is possible having a greater percentage of factory made components.

2.2.3. *Modularity – learning economies*

Gen IV defines "modularity like" the idea of construction and deployment of a larger number of standardized units (EMWG, 2005). Allowed by the smaller size and lower power of SMRs, the modularity approach reduces the requirements for more expensive and time consuming on site construction and also allows a greater standardization. The design of SMRs embodies specific technical solutions (e.g. the integral layout, the broader Safety-by-Design solutions allowed by the size reduction, etc.) which are not applicable to current or classical LR designs. Above all the SMRs rely upon a technical concept that includes the supply of standardized components and their assembly and maintenance within the plant site, with a reduction of investment and operating costs. It is worth mentioning that the standardization of SMR components, along with the smaller size of units, is a necessary condition for suppliers to replicate in a factory the production of SMR units and to reap the learning economies. It is well known that a Nth-Of-A-Kind (NOAK) plant costs less than a First-Of-A-Kind (FOAK) because of the lessons learned in the construction and deployment of earlier units. The learning curve generally flattens out after 5–7 units. Comparing a SMR and a LR, the NOAK is reached with less MWe installed for SMRs than LRs.

Learning is definitely an advantage for the SMRs in the early stages of the market, to be eventually equalized as the market for both designs matures. In addition to the above "worldwide" learning (it does not matter where the units are built to reach the Nth) there is also an additional "on site" learning, obtained from the construction of successive units on the same site. This important portion of the "total learning" take to a big advantage for the SMRs when, in a same power comparison, a site with one LR is compared with a site with many SMRs.

Aside from learning economies related to a high cumulated number of supplied SMR units, the mentioned technical benefits will hopefully allow the SMRs to experience smaller average generation costs, given the plant size (technical progress economies).

Still, modularity is considered a common factor, because it is also employed in the most recent large plants designs and thus has to be comparatively evaluated.

2.2.4. *Multiple units at a single site*

If the demand is growing locally, SMRs allow the investors to make incremental capacity additions in a pre-existing site. This leads to co-siting economies: the set-up activities related to siting (e.g. acquisition of land rights, connection to the transmission network) have been already carried out; certain fixed indivisible costs can be saved when installing the second and subsequent units. The larger the number of SMR co-sited units, the smaller the total investment costs for unit. This factor is applicable also when a new site is opened. Also in this case the obvious advantages are the sharing of infrastructure and the fix costs (like license and insurances), the better utilization of site material and the sharing of human resources. Of course, more SMR units are deployed for the same amount of power attained with larger reactors, but both small and large plants can be deployed in multiples at a single site and in fact, several multi-unit sites with thousands of installed MWe do exist. Thus, while in principle the factor favors the SMRs, a case-by-case evaluation must be done.

2.2.5. *Front end investment*

Specific characteristics of SMRs such as smaller size, simpler design, increased modularization, higher degree of factory fabrication and serial fabrication of components lead to a shorter construction time. In fact current projected schedules for SMRs are three years for the FOAK, projected to be reduced to as little as two years for the NOAK. The unit cost of a SMR is of course a fraction of the cost of a larger plant (several hundred million, rather than a few billion dollars). This reduction can be "the" critical factor for a utility or country with limited resources, therefore for a given size the multiple SMRs allows a larger number of investors than LR to enter the nuclear generation sector.

Table 2 synthesises the distribution of the mentioned benefits across the factors.

All the above factors should be taken into account when comparing SMRs and LRs. In this paper we focus on factors with major effects on the generation costs.

A parametric model will allow the user to analyze the sensitivity of SMRs differential profitability to a number of exogenous elements like market and production setting.

3. A generalised model for SMR generation cost

The main target of the model is the evaluation of the production cost of electricity (e.g. €/MWh) corresponding to the plant to be analysed, given a cash flow expenditure during the whole plant life. This cost is generally referred as the Levelized Unit Electricity Cost (LUEC). The model has to be flexible and sufficiently open to receive data from new reactor technology solutions (e.g. Generation IV, INPRO, GNEP) as well as from different international scenario (insurance, tax and account management rules should be customisable to the country). Moreover, the module should consider both closed, partially open or open fuel cycles.

In general, the cost generation model is a total cost function defined at the plant level. In the short-run the total cost *TC* [€] is

Table 2
NPP features and their positive (+) and negative (−) effects: expected contribution to SMR differential profitability.

NPP feature	Generation costs	Financial costs	Market opportunity
SMR ad hoc factors			
Scalability		Investment deferral (+)	Market matching (+)
Investment flexibility		Reduced risk premium (+)	Market matching (+)
Easier plant-grid matching			Market suitability (+)
New design strategy and solutions	Technical progress economies (+)		
Cogeneration			Market suitability (+)
Mass production economies	Mass production economies (+)		
SMR&LR common factors			
Size	Economies of scale (−)		
Modularization	Factory fabrication economies (+) Learning economies (+)		
Modularity	Learning economies (+)		
Multiple units at a single site	Co-siting economies (+) Learning economies (+)		
Front end investment			Reduced entry barriers (+)

a function of the supplied quantity q [MWh], the unit size S [MWe], the specific reactor technology T (e.g. whether LR or SMR) and a set $\boldsymbol{X}$ of other technical and financial factors:

$$TC = TC(q; S, T, \mathbf{X}) \tag{1}$$

Indeed, economies of scale, mass production economies, factory fabrication economies, learning factors, co-siting economies and the economic effects of innovation by design can be modelled deploying variable $\boldsymbol{X}$ and thus expanding Eq. (1). As a first step, we assume that the cost function is separable into the total capital cost function and the total operating cost function. Once that the analytical properties of the cost functions are identified, different functional forms can be specified, and their parameters can be estimated through statistical techniques or calibrated through numerical simulations. The model can then be validated against costs realised by pre-existing NPPs.

3.1. Economies of scale

The hypothesis of decreasing average costs in the construction domain is motivated by the presence of unique set-up costs in investment activities (e.g. siting activities, licensing); economies of scale may also result from the poorer operating efficiency of smaller plants (lower thermal efficiency, less personnel specialization). As far as the capital costs are concerned (i.e., costs incurred for the initial construction), economies of scale can be defined as follows. Given total capital costs TC^I [€] as a function of, among other factors, the unit size S [MWe], the total capital cost elasticity to the size of generating units is:

$$n^C = \frac{\partial TC^I / TC^I}{\partial S / S} \tag{2}$$

If the n parameters are smaller than 1, economies of scale exist in investment or operation and maintenance; the closer the n value is to 0, the larger the economies of scale.

Costs incurred after initial construction include the following items: fuel; plant operating and maintenance expenses; capital expenditures related to facility additions/modifications (ORNL, 2003). The latter are investment costs in nature and should be included in construction costs.

The Operation and Maintenance (O&M) costs, net of fuel costs, may exhibit increasing return to the plant size. Usually O&M costs include (Bowers et al., 1987): on site staff, offsite technical support, pensions and benefits, supplies, consumables and expenses, maintenance materials, nuclear insurance premiums, nuclear regulatory fees, other administrative and general expenses. It is worth mentioning that they are a relatively small share of total costs at the plant level. O&M economies of scale can be defined as follows. Given total O&M costs TC^{OM} [€] as a function of the plant size S [MWe], the total O&M cost elasticity to the plant size is:

$$n^{OM} = \frac{\partial TC^{\mathrm{OM}} / TC^{\mathrm{OM}}}{\partial S / S} \tag{3}$$

Engineering studies report that economies of scale exist and are quite strong in investment and O&M costs. Bowers et al. (1983) reviewed the previous techno-economic estimates of nuclear investment costs at the plant level. The results are quite scattered, due to methodological and sample differences; nonetheless the literature converges to estimate n^I parameters that are consistent with the hypothesis of economies of scale (Table 3). Economies of scale in investment activities are found to hold at a more disaggregated level, as shown by DOE (1988) (Table 4). The average investment cost for individual items are on average decreasing with the plant size; some set-up, indivisible resources as land rights, structures or electric systems play a major role.

Bowers et al. (1987) estimate and validate a n^{OM} parameter for LWR plants; several O&M cost items are shown to follow an economies of scale law and the same holds true for the aggregated O&M costs.

The notion of strong economies of scale at the plant level in nuclear generation is to some extent criticized by more recent econometric studies.

In their study on economies of scale at the plant level, Marshall and Navarro (1991) revise the widespread concept of "overnight costs". It has to be recalled that Overnight Cost usually refers to the hypothetical, estimated, capital (construction) cost of a facility, either a power plant or a transmission line, in current-year dollars, assuming the facility could be built overnight. This is usually the starting point for developing a facility cost estimate, because the engineer estimates how much material and how many man-hours would be required to fabricate and build the facility, all in current-

Table 3
Economies of scale in investment costs.

Author	Year	Scale exponent n	Note
[–]	1968	0.75	LWR total cost
[–]	1968	0.51	Total cost
McNelly and Koke	1969	0.64	Total cost
Bennett Bowers	1971	0.68	Total cost
Leedy and Scott	1973	0.4	LWR direct Cost
Davis	1975	0.47	BWR total cost
Mandel	1976	0.46	LWR total Cost
Woite	1976	0.71	Direct and indirect costs
Comtois	1977	0.86	LWR total costs
	1977	0.76	LWR total costs
Mooz, Rand	1978	0.8 / 0.5 / 0.7	LWR regression analysis of historical data; marginal statistical significance. Different assumptions
Mooz, Rand	1979	1	LWR regression analysis of historical nuclear plants; no statistical-significant economies of scale was found
Crowley	1978	0.45	Direct and indirect costs
Woite	1979	0.4	PWR direct and indirect costs
Gehring	1979	0.24	LWR direct and indirect costs
	1979	0.49	Total costs. It was used CONCEPT CODE 5
Fjeldsted	1980	0.59	Total costs; source: F.S. Aschenr, Planning Fundamentals of Thermal Power Plants, John Wiley and Sons, New York (1978) Include allowance for escalation and interest during construction
McMahon	1980	0.43	Direct and indirect costs
Nieves et al., Battelle	1980	0.25	Regression analysis of historical data; direct and indirect costs and constant dollar interest during construction. For nuclear units Komanoff found a 13% cost reduction in €/kW(e) for doubled size
Komanoff	1981	0.8	Regression analysis of historical data; direct and indirect costs
McMahon	1981	0.43	Total costs; 0.92 for 100–600-MW(e) oil fired units
Crowley	1981	0.4	Direct costs
Nobile and Kettler	1982	0.63	Regression analysis of historical data; direct and indirect costs and constant dollar interest during construction.
	1982	0.53	LWR Direct and indirect costs.
	1982	0.63	LWR Engineering cost estimates
Perl	1982	0.49	Regression analysis of historical data

Source: Bowers et al. (1983).

Table 4
Economies of scale in individual investment items.

Cost items	Scale exponent n
Direct costs	
Land and land rights	0.00
Structures and improvements	0.59
Reactor/boiler plant equipment	0.53
Turbine plant equipment	0.83
Electric plant equipment	0.49
Miscellaneous plant equipment	0.59
Main condenser heat rejection system	1.06
Indirect costs	
Construction services	0.69
Home office engineering and services	0.60
Field office engineering and services	0.69
Owner's costs	0.64
Cost-weighted average	0.64

Source: DOE (1988).

year dollars. In the nuclear sector the total overnight cost is the base construction cost plus applicable owner's cost, contingency and first core costs. Because of power plants may take several years to get permits and other required approvals, and may take other years to construct, escalation/inflation, interest on capex and other factors working on the overnight cost cause the final Capital Cost of the plant to actually be higher than the overnight cost.

Under a definition of capital costs for investment more related to the economic theory, a set of Japanese nuclear plants cease to show increasing returns to plant size for the investment activities. Rungsuriyawiboon (2004) uses advanced estimation techniques to sum up investment, fuel and operating costs for a sample that is more up-to-date than those of previous studies (i.e. US nuclear plants that are observed over the period 1986–1998). Most of nuclear utilities are shown to have overinvested over time; while short-run economies of scale are very strong, long-run economies of scale, that is economies of scale net of the effects due to slack capacity saturation, are present but are by far weaker (similarly to findings obtained by Rhine, 2001, for a set of US electric utilities at the firm level).

Since the pioneering econometric study by Christensen and Green (1976), a parallel line of research empirically explores costs at the firm electric (utility) rather than plant level. Most utilities that have in their generation portfolio nuclear units are multi-plant; cost savings other than plant-level economies of scale may result from the reliance upon common corporate resources. Kamerschen and Thompson (1993) estimate that the nuclear generation costs, net of the so-called "politically determined" costs (e.g. licensing delays), may outperform fossil-fuel generation costs. Thompson and Wolf (1993) confirm that differences exist and enlighten the role played by the region of plant location. Rhine (2001) finds that economies of scale at the firm level are overestimated by previous works: with both nuclear and fossil-fuel technologies, electric utilities tend to overinvest.

In conclusion, a wide body of traditional techno-economic studies provides us with evidence of strong economies of scale in both investment and operation. Yet the recent applied economic research emphasizes that this result may be partially related to biased measures of investment costs or to past over-investments, that frequently result in excess plant capacity.

3.2. Learning economies and co-siting economies

Learning economies result from the replicated supply of SMR components by the suppliers and from the replicated construction and operation of SMR units by the utilities and their contractors. In turn, the replication and related learning economies are the joint effect of small size and standardization, as discussed and modelled by Lester and McCabe (1993), David and Rothwell (1996a,b) and Carayannis (1996). Irrespectively of the plant size, this allows the investors which adopt SMRs to hopefully experience lower average investment costs and lower average operating costs than investors who adopt LRs.

Let N^S, N^U and N^W be, respectively: the number of SMR units already installed and operated by the utility and its contractors in the site, the number of other units of the same SMR concept installed and operated by the utility and its contractors throughout the same utility's plants in the past years, the number of units of the same SMR concept produced by the supplier in the past years and offered to other utilities throughout the world. The sum is equal to the total number of units of the same SMR concept already supplied and constructed, N. The total capital costs TC^I [€] is a function, among other things, of the plant size S [MWe], the cumulated numbers of world, utility and site units N^W, N^U, and N^S; the total investment cost elasticity to N^i, $i = \{W, U, S\}$, is:

$$l^i = \frac{\partial TC^I/TC^I}{\partial N^i/N^i}, \quad \text{for } N^i > 1 \tag{4}$$

If the l^i parameter is smaller than 0, given the plant size, economies of learning are said to exist in investment costs. Nonetheless, it is well known that the learning effects are especially strong for early units and are diminishing with respect to the cumulated number of installed units; accordingly:

$$l^i \leq 0, \quad \text{and} \quad \frac{\partial^2\left(TC^C/TC^C\right)}{\left(\partial N^i/N^i\right)^2} \geq 0 \tag{5}$$

Two arguments are worth being made on the role played by the accumulated numbers of SMR installed units in driving down the investment costs.

First, the one "co-siting economies", consisting in fixed and semi fixed costs shared by a number on SMR units greater than the number of LRs installed to have the same power.

Second, the SMR units that are installed in a certain site allow the firm to benefit from three-level learning economies, that is, from cost-reducing effects related to the supplier's, utility's and plant organization's cumulated experience. The SMR units that are installed in the utility's other sites bring in learning economies that are originated by the cumulated experience of both supplier and utility. As a consequence, we preliminarily propose that the learning path is pursued at a faster rate when an additional unit is installed in the same site, rather than in other sites operated by the same utility or by other utilities, due to extra learning effects that are related to the experience of the site personnel and to the local network of contractors – see Zimmerman (1982) and Carayannis (1996).

$$l^S \leq l^U \leq l^W \leq 0 \tag{6}$$

where:

l^S = site learning economies;
l^U = utility learning economies;
l^W = world learning economies.

Similar indicators can be defined for learning economies in O&M activities, starting from the definition of total O&M costs TC^{OM}. Operating learning economies can be experienced at site and utility level; the operating cost elasticity to N^j, $j = \{U, S\}$, is defined through a l^j parameter, similar to Eq. (4).

3.3. Design strategies and innovative solutions

Shepherd and Hayns (1991), Schock et al. (2001) and Miller (2005) illustrate why the technical solutions that are embodied by the SMR design are able to reduce the investment and operating costs, for a given plant size. The most relevant elements of the SMR concept is the standardization of components and a broader safety-by-design approach. Standardization is at the origin of more efficient supply, construction and operation (see Langlois, 2002 for a general discussion of the effects of standardization through design modularity); furthermore it is worth mentioning that the standardization enables suppliers and utilities to reap more rapidly the learning economies (David and Rothwell, 1996a,b; Carayannis, 1996).

At this stage of the research, the nature and role of standardization have still to be analysed and modelled.

The safety-by-design approach leads to elimination, or substantial simplification, of both the active and passive safety systems, compared to the reference plant, therefore this reduction and simplification of components allow to reduce the overnight cost thanks to both reduced labour and cheaper equipments. This aspect has been quantified in Par. 5.1 as the Modularity and Design solutions factor ϑ_{MD}.

4. SMR generation cost – empirical methods

4.1. Engineering cost analysis

The generation costs can be grouped into four main items:

i) Capital costs;
ii) O&M costs;
iii) Fuel and Fuel Cycle costs;
iv) Decontamination and Decommissioning (D&D) costs.

There are studies (Mackerron et al., 2006), that give an indicative range representing the proportion for the main cost items (Table 5).

The adaptability feature is of paramount importance since a large part of the SMRs are still in the design phase, hence detailed "bottom up" cost estimates are not yet available, but will be as the projects develop. Thus a simplified "top down" estimation of costs is needed. Among the available techniques for a simple estimation of the costs in the nuclear sector, those included in the French SEMER code (Nisan et al., 2003) seems to be compliant with the objective. The model has been developed to evaluate the economic impact for different innovative reactors and esteems the new generation reactor costs, for which detailed information are not yet available, by means of equations based on the following base input set:

- Reactor power,
- Number of units on site,
- Number of units to be built in series,
- Construction time,
- Plant lifetime,
- Discount rate and interest rate,
- Thermal cycle efficiency,
- Labour cost,
- Load factor.

Table 5
Cost ranges according to the NERA study.

Account	Range
Capital cost	60–75%
Fuel cost	5–10%
Operation and maintenance cost	8–15%
Final or decommissioning cost	1–5%

Source: Mackerron et al. (2006).

Another study (Sultan and Kattab, 1995) evaluates in a parametric way the generation costs as a sum of two components: the first item is a function of the installed electric power (main NSSS and BOP components), the second item is independent from the size (e.g. service buildings, auxiliary systems, labs, etc.).

At a preliminary stage in the development of the generation cost model, it seems reasonable to use simplification features similar to those adopted by the Gen IV GIF Economic Modelling Working Group (EMWG, 2004a):

i) the costs can be broken down into two basic phases of the plant life: the construction phase and the operational phase; since detailed costs are usually not available, a given expenditure or cash flow profile (e.g. the cumulative expenditure "S-curve") during the design/ construction/start-up/financing period is assumed, leading to a "total capitalised cost";
ii) at a preliminary stage, escalation cost factors is not quantified. The escalation is reduced by the shorter construction time and a greater percentage of factory made modules, both due to a broader modularization typical of the SMR design. On the other hand the modern SMRs have never been built and this fact increases the risk of cost escalation. Considering these aspects a deep study about the different role that the escalation assumes for SMRs and LRs should be performed in the future;
iii) open fuel cycles and cycles with limited or full recycle can be modelled, but only two types of fuel are adopted, the initial core fuel and the reload fuel; the unit costs of fuel cycle services and materials are identical in constant currency for the life of the plant.

Since the fuel and fuel cycle cost modelling can be treated in a complex and detailed manner (as in OECD/NEA, USCEA/NEI models) and thus can represent a not homogeneous burden when compared with the other models, the same strategy equilibrium followed in EMWG (2004b) and DANESS code (Van Den Durpel et al., 2003, 2005) could be adopted.

Hence the main macro-items for the cost breakdown structure are (EMWG, 2004a; DOD, 1983):

- R&D and design costs,
- License and permits,
- Construction,
- Interests,
- O&M,
- Fuel,
- D&D.

The generation cost model will provide an estimated value for the LUEC (in currency/MWh), i.e. the value of the total cost for construction and operation of a nuclear power plant all over its economic life, expressed in constant annual values.

4.2. Specification of the cost function

As already discussed in Par. 3, the output of the cost generation model will be a cost function at the plant level. In order to empirically estimate the cost advantages/disadvantages of SMRs with respect to LRs, our starting point is the formulation of a specific functional form for a derived function, namely the average cost function.

In particular, for the sake of exposition, hereby we focus on the specification of Average Capital costs AC^C [€/MWe]. Similarly to Eq. (1), they can be expressed as a function of the unit size S [MWe], and a set $\boldsymbol{X}$ of factors that characterize SMRs with respect to LRs:

$$AC^C = AC^C(S, \mathbf{X}) \quad (7)$$

A more general model also includes the supplied quantity q [MWh]. Yet if we assume that the load factor is constant across installed plants, q is perfectly correlated to S and we will not include it in the right hand-side of the equation.

A convenient approximation of the general Eq. (7), insofar as it allows to derive elasticities (i.e., the normalised effect of independent variables on the dependent variable) in a very simple way, is the following log-linear function, with AC_0^C, S_0, and $\boldsymbol{X}_0$ as the approximation point:

$$\frac{AC^C}{AC_0^C} = \left(\frac{S}{S_0}\right)^{\alpha_{ES}} \cdot \left(\frac{X_1}{X_{1,0}}\right)^{\alpha_1} \cdots \left(\frac{X_N}{X_{N,0}}\right)^{\alpha_N} \quad (8)$$

Note that the i-th parameter α_i is the elasticity of average costs with respect to the related i-th independent variable, i.e. the normalised effect of a change in the independent variable (the normalised partial derivative) on the dependent variable. Note that α_{ES} is the economies of scale exponent for average costs, $\alpha_{ES} = n - 1$, with n defined as the scale exponent for total costs, as in Eq. (2). If the independent variable is continue (such as the size):

$$\alpha_i = \frac{\partial AC^C / AC^C}{\partial X_i / X_i} \quad (9)$$

given S and other factors $\boldsymbol{X}_{-i}$.

If the independent variable is discrete (such as the number of units in the site):

$$\alpha_i = \frac{\Delta AC^C / AC^C}{\Delta X_i / X_i} \quad (10)$$

given S and other factors $\boldsymbol{X}_{-i}$ as well.

Factors $\boldsymbol{X}$ that have been taken into account are:

- *Replication, Standardization*: variables N_n = progressive number for plants in the site, and N_{World} = total plants in the world (outside the site considered), parameter (α_l);
- *Scalability – Co-siting*: variable N_n = progressive number for plants in the site, parameter (α_{CS});
- *Scalability – Financial aspects*: variable *WACC* (Weighted Average Cost of Capital) = cost of capital [%], parameter (α_F);
- *Modularity and Design solutions*: variable MD = degree of modularity and innovative design solution characterizing the plant, parameter (α_{MD}).

In order to compare the average cost of a SMR site and a LR site, we simulate the ratio $AC^C{}_{SMR}/AC^C{}_{LR}$; that is, we compute the overall saving factor:

$$\delta = \frac{AC^C(S_{SMR}, N_{nSMR}, N_{WorldSMR}, WACC_{SMR}, MD_{SMR})}{AC^C(S_{LR}, N_{nLR}, N_{WorldLR}, WACC_{LR}, MD_{LR})} \quad (11)$$

This corresponds to simulate the overall effect of a $(\boldsymbol{X}_{i,SMR} - \boldsymbol{X}_{i,LR})/\boldsymbol{X}_{i,LR}$ variation for each independent variable.

All the independent variables contribute to determine δ. E.g. the effect of a smaller size (S_{SMR} rather than S_{LR}), other things being equal (i.e. when factors $\boldsymbol{X}$ are held constant and equal to $\boldsymbol{X}_{LR}$), is:

$$\vartheta_{ES} = \frac{AC^C(S_{SMR},\ X_{SMR})}{AC^C(S_{LR},\ X_{LR})} = 1 + \alpha_{ES}\left(\frac{S_{SMR} - S_{LR}}{S_{LR}}\right) \quad (12)$$

The overall effect, i.e., the saving factor δ for the SMR solution with respect to the LR one, is then obtained by multiplying the parameters ϑ_i:

$$\begin{aligned}\delta &= \frac{AC^C(S_{SMR},\ N_{nSMR},\ N_{WorldSMR},\ WACC_{SMR},\ MD_{SMR})}{AC^C(S_{LR},\ N_{nLR},\ N_{WorldLR},\ WACC_{LR},\ MD_{LR})}\\ &= \vartheta_{ES} \times \vartheta_l \times \vartheta_{CS} \times \vartheta_F \times \vartheta_{MD}\end{aligned} \quad (13)$$

where ϑ_{ES}, ϑ_l, ϑ_{CS}, ϑ_F, ϑ_{MD} are the economies of scale, learning, co-siting, financial and modularity & design factors, respectively.

5. An example of cost estimation for SMRs

5.1. Capital costs

The empirical model described in Par. 3 has been adopted to assess the cost differences between a SMR solution and a LR solution:

- SMR solution: a pack of four 335 MWe SMRs (IRIS design);
- LR solution: a single unit 1340 MWe reactor.

This allows to gauge the most important differential aspects involved, i.e. the ϑ factors in Eq. (13).

Once the average cost for a LR is assumed always equal to one, the model computes a number greater than or less than one, referred to a SMR, for each key factor. The multiplication of these coefficients gives a final dimensionless number representing the saving factor δ on capital cost for the SMR solution with respect to the LR solution. Thus it quantifies a normalised specific capital cost [€/kWe] for a site with a given number of SMRs, compared to a site with one or two large size reactors, being the station power equal.

Before considering the *ad hoc* and *common* factors, a basic scale parameter for the SMR has to be estimated. According to Eq. (8), the structure of the model considered is:

$$AC_{SMR}^C = AC_{LR}^C \times \left(\frac{S_{SMR}}{S_{LR}}\right)^{\alpha_{ES}} \quad (14)$$

In order to quantify the economies of scale exponent α_{ES}, an historical analysis has been made from different literature sources to find consistent model and values, identifying minimum (“High economies of scale”), expected (“Standard economies of scale”) and maximum (“Low economies of scale”) exponents.

Almost all the references (as in Table 3) indicate an overall scale exponent between 0.5 and 0.7, with an average value around 0.6.

It is possible to compute in a more accurate way the economies of scale value for the capital cost considering its breakdown costs. By dividing the overall cost in its main accounts and considering for each i-th account its economies of scale exponent (n_i) it is possible to better assume the overall exponent. Concretely the following algorithm is implemented:

1. Assume the breakdown cost for the Large Size reactor;
2. Compute the economies of scale for each account using the same structure of Eq. (14) and the opportune n exponent (main references for the n_i exponents are Phung, 1987 and GEN IV, 2005);
3. Sum the accounts’ values to compute the total capital cost for the SMR [€]. The SMR is now characterized by a size S_{SMR} and an average cost C_{SMR} (total capital cost/Size);
4. Compute the general exponent α_{ES} used in Eq. (14) with the following formula:

$$\alpha_{ES} = \frac{\ln \frac{AC^{C}_{SMR}}{AC^{C}_{LR}}}{\ln \frac{S_{SMR}}{S_{LR}}} \tag{15}$$

The result from this account-by-account analysis, led to an equivalent exponent value of $\alpha_{ES} = 0.619$, that means a site with one 335 MWe SMR has an average cost [€/kWe] around 70% greater than a site with one 1340 MWe LR (Table 6, Fig. 1).

At this point, there are several factors that can change the gap resulting from the economies of scale factor, $\vartheta_{ES} \approx 1.70$. Among the different *ad hoc* and *common* factors described in Par. 2, four specific factors δ have been taken into account and estimated, as in Eq. (13).

The rationale for a global cost reduction is that all the parameters except ϑ_{ES} are<1 (Fig. 2).

The learning factor ϑ_l has been estimated by adopting the following model, considering the equipment (C_{eq}), labour (C_{lab}) and material (C_{mat}) costs:

$$\begin{cases} \overline{\vartheta}_l = \sum_{n=1}^{f} \left[\frac{C_{eq}+C_{lab}+C_{mat}}{f} \times C_n \right] \\ C_{eq} = K_{eq} \times (N_{World} + N_n)^{-\alpha} \\ C_{lab} = K_{lab} \times (N_{World} + 1)^{-\beta_2} \times (N_n)^{-\beta_1} \\ C_{mat} = K_{mat}(N_n)^{-\gamma} \end{cases} \tag{16}$$

where:

α = learning in factory equipment;
β_1 = labour learning in the site;
β_2 = labour learning in the world;
γ = learning in use of material;
n = index for units in the site;
f = final number for units in the site;
C_n = nondimensional financial factor for n-th plant;
N_n = progressive number for plants in the site;
N_{World} = total plants in the world (outside the site considered);
K_{eq} = percentage for equipment cost in the First-Of-A-Kind (FOAK) unit;
K_{lab} = percentage for labor cost in the FOAK unit;
K_{mat} = percentage for material cost in the FOAK unit.

The learning factors α, β, γ refer to "on site" and "world" type learning and are derived from EMWG (2005) and experts elicitation. The K percentages are derived from typical cost breakdown of LWRs and experts elicitation as well. Since the FOAK costs are considered, N_{World} is assumed 0 while N_n is 1 for the LR and 4 for the SMR.

This approach allows to consider in a differential way the learning coming from the site experience and world experience. In fact, considering the labour account, the site learning is stronger than the world learning since the same contractors are realistically involved; otherwise when the same reactor is built in different locations, it is conservative to assume a smaller learning since workers and contractors could change. This aspect is considered in the C_{lab} coefficient.

On the other hand, when the equipment account is considered, the site location is not relevant, in fact it is reasonable to assume that the same suppliers provide their components of the equipment to each site. Since the location is not differential the C_{eq} expression weights in the same way the reactors built inside and outside a certain site. The C_{mat}, conservatively, assumes a saving only for the reactors built in the same site: it assumes that changing the site, the learning referred to the material is lost. This assumption is consistent with the experience in building nuclear power plants.

The C_n factor, taking into account the cost escalation due to the time frame, has been considered equal to 1.

The estimation shows that for the four units case, the cost reduction is between 8 and 10%. The 8% value was conservatively chosen, therefore δ_l is equal to 0.92.

Table 6
Estimation of scale exponents, on an historical (*High*, *Normal*, *Low*) and on a cost breakdown (*Calc.*) basis.

	High	Normal	Calc.	Low
Scale exponent α_{ES}.	0.50	0.60	*0.62*	0.70
Average cost ratio ϑ_{ES}	2.00	1.74	*1.70*	1.52
Difference %	+100%	+74%	*+70%*	+52%

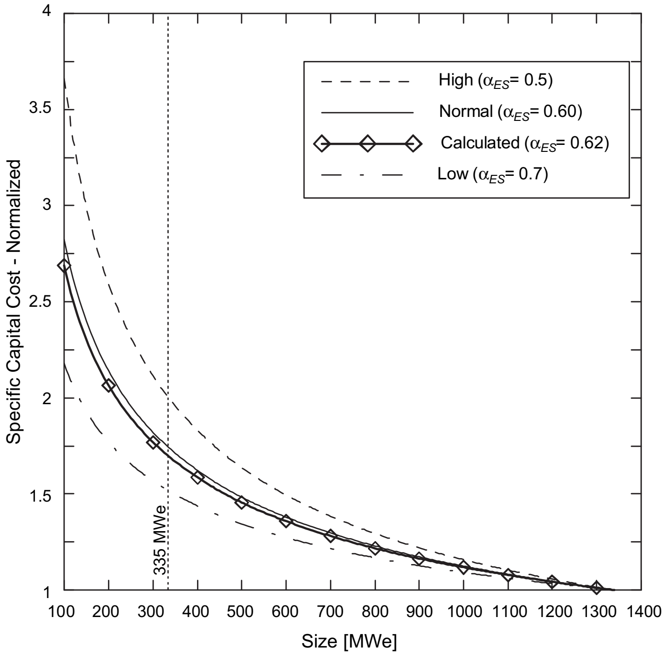

Fig. 1. Economies of scale effect: trend of the NPP capital cost with size (ref.: NSCC = 1, for size = 1340 MWe).

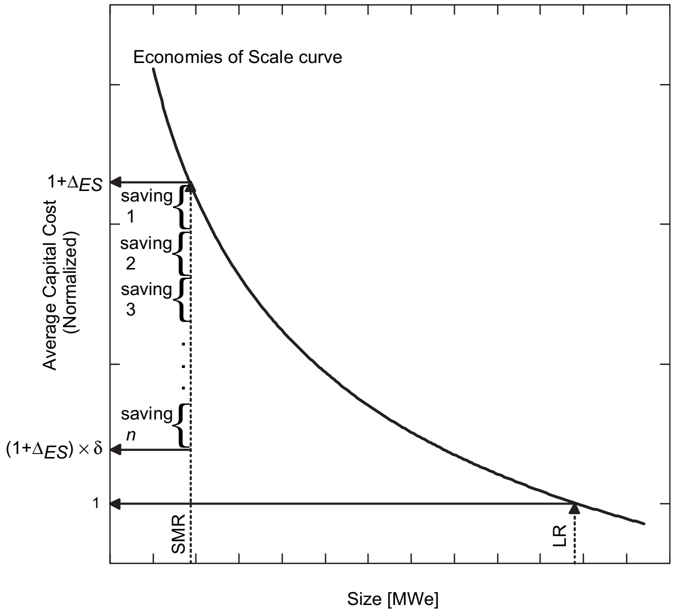

Fig. 2. Positive effect of *ad hoc* and *common* factors affecting SMR capital cost.

The co-siting, or multiple units on the same site, factor δ_{CS} has been estimated by taking into account IAEA (2005) and other data (Kadak, 2002; Shepherd and Hayns, 1991), by eliminating learning effects. Since the indirect costs are the main part of cost affected by the co-siting factor, a breakdown cost analysis has been performed. Considering the indirect cost it is important to underline that for the cost of the second unit in the site, or more generally for the "marginal units", there is a saving equal to 42% (due to not recurrent costs, as stated in Par. 2.2). Therefore it is possible to assume this value as an asymptotic saving achieved with infinite units in the site.

In a real situation n units will be in the site, thus assuming equal to 1 the cost for a stand alone unit, the total indirect cost for the n units will be:

$$C_{ind} = 1 + (n-1) \times (1 - AS) \tag{17}$$

where C_{ind} is the total indirect cost for n plants on a single site and AS is the asymptotic saving.

Therefore the saving in the indirect cost for a site provided by n units is the ratio between C_{ind} and the total indirect cost for n plants on n different sites, each one hosting a single reactor:

$$\vartheta_{CS,ind} = \frac{1 + (n-1) \times (1 - AS)}{n \times 1} \tag{18}$$

Since the indirect costs do not consider the structure of the reactor, this value is the same for both a stand alone and a "twin unit" configuration, i.e. a couple of identical nuclear reactors on the same site.

Focusing on direct costs, it has been conservatively assumed a saving only in a case of "twin units". This value is equal to 5.3%. Since the indirect costs account for the 34% of the total cost and the direct cost for the remaining 66%, for the four versus one plant comparison, it was evaluated that a 14% saving exists for the multiple SMRs, therefore δ_{CS} is equal to 0.86. This value is consistent with literature values.

The next two effects, construction schedule and matching of supply to demand (or "timing"), were evaluated together, assuming a construction schedule for the LR and SMRs of five and three years respectively and calculating the cumulative expenditures for the two cases. A 6% savings was estimated for the shorter construction time coupled with the SMRs capability of better following the demand curve, therefore δ_F is equal to 0.94.

The main design-related characteristics for IRIS (Carelli et al., 2004) are the elimination of all large primary piping and of vessel head and bottom penetrations, as well as of several safety systems such as the high pressure injection emergency core cooling system, due to the Safety-by-Design approach which eliminates several postulated accidents, the integration within the reactor pressure vessel of the main primary components i.e. the modular steam generators and the main recirculation pumps, a compact containment and a lower amount of commodities.

In order to give an estimate of δ_{MD} (considering both the modularization and the Safety-by-Design approach), ORNL (Reid, 2003) proposes an empirical curve correlating the size with a reasonable saving. The value achieved considering a generic 335 MWe reactor is 13%.

After a deep account-by-account analysis of the IRIS reactor, a conservative evaluation of these effects indicates a 17% cost saving, therefore δ_{MD} is equal to 0.83.

When the various factors are combined, a pack of four 335 MWe SMRs has a capital cost only 5% higher than the single unit 1340 MWe reactor (Table 7).

Some sensitivity studies were also carried out, to allow also the LR to take advantage of multiple units on site and to investigate the effect of "worldwide" type learning. The reference case reported here and yielding a cumulative factor $\delta = 1.05$, considered four IRIS vs. one large plant on site, with no prior experience for either (i.e., no worldwide learning). A case of eight IRIS and two large plants on site, still with no prior experience yielded a total factor $\delta = 1.16$, reflecting the proportionally higher effect of two large units on site. On the other hand, a case of four IRIS and one large plant on site, but with a prior worldwide experience of 2680 MWe for both (which means two large plants and eight IRIS) yielded a total factor of 1.00, reflecting the much larger learning deriving from the higher number of units (Table 8). Other sensitivity cases fell within the 1.00–1.16 range.

Notwithstanding this evaluation is approximated and few factors were considered, it can be concluded that the capital cost of SMRs can reasonably be quite similar to that of LRs, the same installed power being considered.

5.2. Operation and maintenance costs

After the capital cost, in developed countries usually the most important account in the life cycle cost for a nuclear power plant is the O&M cost. Considering Table 5, it seems that the O&M costs are a small part of the total cost for a nuclear power plant. However it becomes very important for the yearly economic and financial sustainability of the plant all along its life cycle: cases are reported where nuclear power plants have been closed due to a dramatic increase in the operation and maintenance costs (DOE/EIA, 1995).

The model used to quantify the O&M cost is based on Bowers et al. (1987) and identifies three main cost categories: labour cost (on site and offsite), material cost (shop supplies), and a third category including other marginal cost items. The model assumes a reference cost for each cost category (estimated from DOE/EIA, 1995), that is adjusted by means of two coefficients. The first one considers the economies of scale effect whereas the second takes into account the number of units built in the same site. The estimation functions for both coefficients use an exponent less than one, due to the nonlinear correlation between the number of units, the size of reactors and O&M costs.

According to the model it is possible to conclude that a site with four SMRs (335 MWe) has an O&M cost 24% greater than a site with one 1340 MWe LR, or likewise a site with three SMRs has an O&M cost 22% greater the a site with one 1005 MWe LR.

Table 7
Quantification of factors evaluated in SMRs/LR comparison.

Factor	SMR/LR capital cost factor ratio		Conceptual reference plant
	Individual	Cumulative	
Large plant	1.00	1.00	Reference LR overnight cost (single unit)
Economies of scale (ϑ_{ES})	1.70	1.70	Reference SMR overnight cost (single unit)
Scalability: Co-siting (ϑ_{CS})	0.86	1.46	Reference SMR overnight cost (multi-unit)
Replication, Standardization: Learning (ϑ_{l})	0.92	1.34	Reference SMR overnight cost (multi-unit, same site MWe, same world MWe)
Scalability: Financial aspects (ϑ_F)	0.94	1.26	Reference SMR Completed cost (multi-unit, same site MWe, same world MWe)
Modularity and Design solutions (ϑ_{MD})	0.83	1.05	New SMR completed cost (modular design and safety-by-design characteristics)

Table 8
Sensitivity analysis on capital costs.

Case	LR (1340 MWe)		SMR (335 MWe)		Results (δ)
	Number plants	World experience	Number plants	World experience	
1 (Standard)	1	0	4	0	1.05
2 (Best)	1	2680 [MWe] 2 Plants	4	2680 [MWe] 8 Plants	1.00
3 (Worse)	2	0	8	0	1.16

It is also important to notice that the model does not consider the specific advantages coming from the SMR technology. A future quantification of them is expected to be able to reduce the gap.

6. Conclusions

SMRs and LRs address different markets and there are many market related factors favouring one versus the other, independently from their capital cost. When however they are competing on the same market the capital cost is not a discriminator and the two types of nuclear plants are practically equivalent under this respect.

The O&M cost increases more than the Capital Cost, but less than how is foreseen by a rough computation with the economies of scale canonical equation. It also represent a small part of the total cost which is composed mainly by the capital cost.

The so-called economies of scale is actually no longer an absolute advantage of LRs since it could be compensated by a variety of other factors, first of all technical innovations fostered by SMR design.

This paper presents only the beginning of the evaluation of the competitiveness of SMRs; expanded and more detailed investigations will follow.

References

Afanasiev, A.A., Bolshov, L.A., Karkhov, A.N., 1997. Economic competitiveness of the new generation of NPPs with NP-500 units in Russia. Nuclear Engineering and Design 173, 219–227.

Bae, K.H., Kim, H.C., Chang, M.H., Sim, S.K., 2001. Safety evaluation of the inherent and passive safety features of the SMART design. Annals of Nuclear Energy 28, 333–349.

Bowers, H.I., Fuller, L.C., 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., 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.

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

Christensen, L., Green, W., 1976. Economies of scale in U.S. electric power generation. Journal of Political Economy 84 (1976), 655–676.

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

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

DOD-Department of Defense, 1983. Life Cycle Cost in Navy Acquisitions. Military Handbook Washington, DC, USA.

DOE-Department of Energy, 1988. Nuclear Energy Cost Database – A Reference Data Base for Nuclear and Coal-fired Powerplant Power Generation Cost Analysis. DOE/NE-0095 USA.

DOE/EIA-Energy Information Administration, 1995. An Analysis of Nuclear Power Plant Operating Costs: a 1995 Update. Report SR/OIAF/95-01 Washington, DC, USA.

EMWG-Economic Modeling Working Group, September 30, 2005. Cost Estimating Guidelines for Generation IV Nuclear Energy Systems. Generation IV Technical Document, REV.2.02 Final. http://nuclear.inl.gov/deliverables/docs/emwgguidelines_rev2.pdf.

EMWG-Economic Modeling Working Group, 2004a. Specification for an integrated nuclear energy economic model. Generation IV Technical Document. http://nuclear.inl.gov/deliverables/docs/imsrev0.1a.pdf.

EMWG-Economic Modeling Working Group, 2004b. A generic EXCEL-based model for computation of the projected levelized unit electricity cost (LUEC) from generation IV reactor systems. Generation IV Technical Document. http://nuclear.inl.gov/deliverables/docs/emwg_excelmod_docu.pdf.

Fukami, M.V.I., Santecchia, A., 2000. CAREM project: innovative small PWR. Progress in Nuclear Energy 37 (1–4), 265–270.

GNEP, 2007. GNEP Steering Group Action Plan – an Action Plan for the Safe. Secure Global Expansion of Nuclear Energy. US-DoE.

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

Hibi, K., Ono, H., Kanagawa, T., 2004. Integrated modular water reactor (IMR) design. Nuclear Engineering and Design 230 (1–3), 253–266.

IAEA, 2005. Annex I: Overview of Global Development of Advanced Nuclear Power Plants. In: Country Nuclear Power Profiles – 2004 Edition, Vienna.

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

Kadak, A.C. Modular Pebble Bed Reactor High Temperature Gas Reactor. In: American Nuclear Society Winter Meeting, Washington, D.C, November 2002.

Kamerschen, D., Thompson Jr., H., 1993. Nuclear and fossil fuel steam generation of electricity: differences and similarities. Southern Economic Journal 60, 14–27.

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.

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

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

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

Lester, R.K., McCabe, M.G., 1993. The effect of industrial structure on learning by doing in nuclear power plant operation. RAND Journal of Economics 24 (3), 418–438.

Mackerron, G., Colenutt, D., Spackman, M., Robinson, A., Linton, E., 2006. The Economics of Nuclear Power. Paper 4 in: Report for the Sustainable Development Commission by Science & Technology Policy Research, SPRU. University of Sussex/NERA Economic Consulting.

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

Miller, K., 2005. IRIS – economics review. In: ICAPP '05 Proceedings. Seoul, Korea.

Mitenkov, F.M., Averbakh, B.A., Antyufeeva, I.N., 2007. Economic effect of the development and operation of serially produced propulsion nuclear power systems. Atomic Energy 102 (1), 42–47.

Nisan, S., Rouyer, J.L., Marcetteau, P., Duflo, D., 2003. SEMER: a simple code for the economic evaluation of nuclear and fossil energy-based power production systems. Nuclear Engineering and Design 221 (1–3), 301–313.

ORNL, 2003. U.S. Nuclear Power Plant Operating Cost and Experience Summaries. NUREG/CR-6577. Oak Ridge National Laboratory, Oak Ridge, TN, USA.

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. Modelling Modularity Impacts on Nuclear Power Plant Costs, ORNL Report.

Rhine, R., 2001. Economies of scale and optimal capital in nuclear and fossil fuel electricity production. Atlantic Economic Journal 29 (2), 203–214.

Rungsuriyawiboon, S., 2004. An Analysis of Cost Structures in the Electricity Generation Industry. CEPA Working Paper 05/2004. University of Queensland, Brisbane, AU.

Schock, R.N., Brown, N.W., 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.

Shepherd, J., Hayns, M.R., 1991. SIR: reducing size can reduce costs. Nuclear Energy 30, 85–93.

Sultan, M.A., Kattab, M.E., 1995. Parametric study for optimization of the specific cost of installed electric power in nuclear plants. Annals of Nuclear Energy 22 (9), 621–628.

Takizawa, S., 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.

Tewari, P.K., Rao, I.S., 2002. LTE desalination utilizing waste heat from a nuclear research reactor. Desalination 150 (1), 45–49.

Thompson Jr., H.G., Wolf, L.L., 1993. Regional differences in nuclear and fossil-fuel generation of electricity. Land Economics 69 (3), 234–248.

Tian, J., 2001. Economic feasibility of heat supply from simple and safe nuclear plants. Annals of Nuclear Energy 28 (11), 1145–1150.

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

Ueda, N., 2005. Sodium cooled small fast long-life reactor "4S" Progress in Nuclear Energy 47 (1–4), 222–230.

Van Den Durpel, L., Yacout, A., Wade, D., Khalil, H. DANESS – dynamic analysis of nuclear energy system strategies. In: Global 2003 Proceedings, New Orleans, November 16–20, 2003.

Van Den Durpel, L., Yacout, A., Wade, D. Development of integrated systems dynamics models for the sustainability assessment of nuclear energy. In: Global 2005 Proceedings, Tsukuba, Japan; October 9–13, 2005.

Yoo, S.-H., Yoo T-, H., 2009. The role of the nuclear power generation in the Korean national economy: an input–output analysis. Progress in Nuclear Energy 51 (1), 86–92.

Zhang, Z., Sun, Y., 2007. Economic potential of modular reactor nuclear power plants based on the Chinese HTR-PM project. Nuclear Engineering and Design 237, 2265–2274.

Zimmerman, M.B., 1982. Learning effects and the commercialization of new energy technologies: the case of nuclear power. Bell Journal of Economics 13 (2), 297–310.

Zrodnikov, A.V., Toshinsky, G.I., Komlev, O.G., Dragunov, Yu.G., Stepanov, V.S., Klimov, N.N., Kopytov, I.I., Krushelnitsky, V.N., 2006. Nuclear power development in market conditions with use of multi-purpose modular fast reactors SVBR-75/100. Nuclear Engineering and Design 236, 1490–1502.